UNIVERSITAT ROVIRA i VIRGILI

TECHNO-ECONOMIC ANALYSIS OF A SOLAR-POWERED SMALL-SCALE REVERSE OSMOSIS DESALINATION SYSTEM ON MADURA'S ISLAND

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Techno-Economic Analysis of a Solar-Powered Small-Scale Reverse Osmosis Desalination System on Madura's Island

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Supervised by

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DECLARATION

We STATE that the present master thesis, entitled "Techno-Economic Analysis of a Solar-Powered Small-Scale Reverse Osmosis Desalination System in Madura's Island" presented by Habibie Muhammad Ega has been carried out under our supervision at CREVER Research Group in the Department of Mechanical Engineering of Rovira i Virgili University.

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Dereje S. Ayou

Alberto Coronas

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List of symbols

$\dot{Q}_f$	Volumetric Feed Flow Rate (L/h)
$\dot{Q}_p$	Volumetric Permeate Flow Rate (L/h)
$\dot{Q}_r$	Volumetric Rejected Flow Rate (L/h)
C_f	Feed Solution Concentration (g/L)
C_p	Permeate Solution Concentration (g/L)
C_r	Rejected Solution Concentration (g/L)
Rej	Rejection Rate (%)
π	Osmotic Pressure (bar)
R	Universal Gas Constant $\left({}^{L.\,bar}/_{K.\,mol}\right)$
T	Water Temperature (°C)
V_b	Molar Volume of Pure Water (L/mol)
X_w	Mole Fraction of Water (mol)
$\Delta\pi$	Differential Osmotic Pressure (bar)
i	Number of Ions (mol)
C_m	Solute Concentration Near Membrane Surface (g/L)
J	Water Flux $\left({}^{L}/_{m^2.\,h}\right)$
L_v	Solvent Permeability Coefficient $\left({}^{L}/_{h.\,bar.\,m^2}\right)$
P_{eff}	Effective Pressure (bar)
P_f	Feed Pressure (bar)
P_p	Permeate Pressure (bar)
P_r	Rejected Pressure (bar)
P_{LP}	Low-Pressure of Pumps (bar)
P_{PX}	Pressure Recovered by PX (Energy Recovery Device) (bar)
μ	Dynamic Viscosity $\left({}^{kg}/_{m.\,s}\right)$

ΔP	Pressure Drop (kPa)
f	Darcy (-)
u	Axial Velocity in Feed Channel $\left({}^{m}/_{s}\right)$
d_h	Hydraulic Diameter (m)
L	Length of RO Membrane (m)
Re	Reynold Number (-)
G	Geometric Spacer Parameter (-)
J_s	Solute Flux $\left({}^{L}/_{m^2.h}\right)$
L_s	Solute Permeability Coefficient (g/L)
B	Constant Parameter Equation (K^{-1})
E_B	Energy Activation (kJ/mol)
k	Mass Transfer Coefficient $\left({}^{m}/_{s}\right)$
Sh	Sherwood Number (-)
D	Diffusivity Coefficient $\left({}^{m^2}/_{s}\right)$
Sc	Schmidt Number (-)
v	Kinematic Viscosity $\left({}^{m^2}/_{s}\right)$
h_b	Thickness of Spacer (m)
sbf	Space between Strands (m)
w	Width of the RO Membrane (m)
$A_{membrane}$	RO Membrane Area (m^2)
I	Current (A)
I_L	Module Photocurrent (A)
I_O	Diode Reverse Saturation Current (A)
q	Electron Charge Constant (Coulomb)
γ	Empirical PV-Curve Fitting Parameter (-)
K	Boltzmann Constant (J/K)

T_c	Module Temperature (K)
V	Voltage (V)
R_s	Module Series Resistance (Ω)
G_T	Total Radiation Incident of PV Array (kWh)
$\eta_{booster}$	Booster Pump Efficiency (%)
η_{motor}	Electrical Motor Efficiency (%)
η_{HP}	High-Pressure Pump Efficiency (%)
η_{PX}	Pressure Exchanger Efficiency (%)
$\dot{W}$	Pumps Work Consumption (kWh)
E_{grid}	Consumed Grid Electricity (kWh)
E_{PV}	Electrical Energy Produced by Solar PV System (kWh)
C_{water}	Cost of Potable Water (US$/m^3)
$C_{electricity}$	Cost of Electricity (US$/kWh)
α	Amortisation Factor (-)
n	Plant Lifespan (year)

List of abbreviations

RR	Recovery Ratio (%)
TMP	Transmembrane Pressure (bar)
ES	Economic Saving (US$)
SEC	Specific Energy Consumption (kWh/m^3)
NPV	Net Present Value (US$)
IRR	Internal Rate of Return (%)
RO	Reverse Osmosis
PV	Photovoltaic
WHO	World Health Organization
ppm	Parts per million
SCOW	Specified Cost of Water (US$/m^3)

CAPEX	Capital Expenditure (US$)
OPEX	Operational Expenditure (US$)

Abstract

The growing global demand for potable drinking water has put scarcity of freshwater resources in various international locations. Indonesia is one of the countries that experienced this kind of issue. One solution is to apply desalination technologies to generate freshwater. Since Indonesia is an island country and surrounds by the sea, desalination technology is suitable to be installed. Reverse osmosis (RO) desalination technology is one of the main leading desalination technologies. This technology used to filtrate seawater and produce freshwater that allowed to be consumed. The energy source of reverse osmosis desalination technology is electrical energy, and it's used to driving pumps that consist of reverse osmosis desalination system. The utility of renewable technology to produce electrical power is one of the technological breakthroughs, and it could be coupled with RO desalination system. Solar energy is abundant in Indonesia, and it could become suitable renewable technology to produce electrical power.

Solar PV is the most convenient technology to be coupled with RO desalination system. In this thesis, studied about PV-RO desalination system technology is conducted. The location for this thesis is Madura, Indonesia, due to the potential of solar PV installation. A simulation model for PV-RO desalination system is formulated and show the potential of this technology at Madura's Island. The results are shown on monthly and annual data. The techno-economic analysis also established in this thesis to the described potential installation of this desalination technology at Madura's Island. All the results are showed the PV-RO desalination system is convenient to applicate to Madura's Island and could become one of the solutions to solve the water scarcity issue.

Keywords: Desalination; Modeling; Photovoltaic system; Reverse Osmosis; Techno-economic analysis,

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1. Introduction

1.1 Background

Water is one of the most abundant resources on the planet, but water scarcity has been one of the main issues around the world [1]. Besides the scarcity, global water sources have been contaminated with the effluent from industry or home appliances. As following to the World Health Organization (WHO), population growth and global warming are the main drives for worldwide water scarcity [2]. According to the World Health Organization (WHO), it is estimated that at least 785 million people around the world got the impact of water scarcity, and two billion people used the contaminated water as their drinking water source. WHO also predicts that the water scarcity issue will increase along the year, especially in developing countries, due to infrequently water treatment or water service plant. In Fig.1, WHO gives an infographic about water scarcity and the conditions in the future.

Fig.1 Infographics about Water Scarcity Impact [2].

From the figures, it can be seen that the water condition around the world is worse with the main problem is the lack of safe water and access to the water itself. More than 25% of the total population around the world will consume contaminated water from surface sources. According to the WHO standard, the healthy water limit of salinity in the drinking water is 500 ppm – 1000 ppm [3], [4]. However, according to the figures, almost 1 billion people around the world doesn't have proper water treatment, and it means the water drinking condition is very poor. Fig.2 is shown the prediction of water stress around the world, and it's indicated the water conditions in developing countries has the worst section. According to the figure, countries in Africa, West Asia, and South-East Asia have the most of the total deaths due to unsafe water consumption. This condition is kept increasing along the time and it's getting worse; especially in the rural and arid areas whereas the water transportation or storage is very less and difficult to be done.

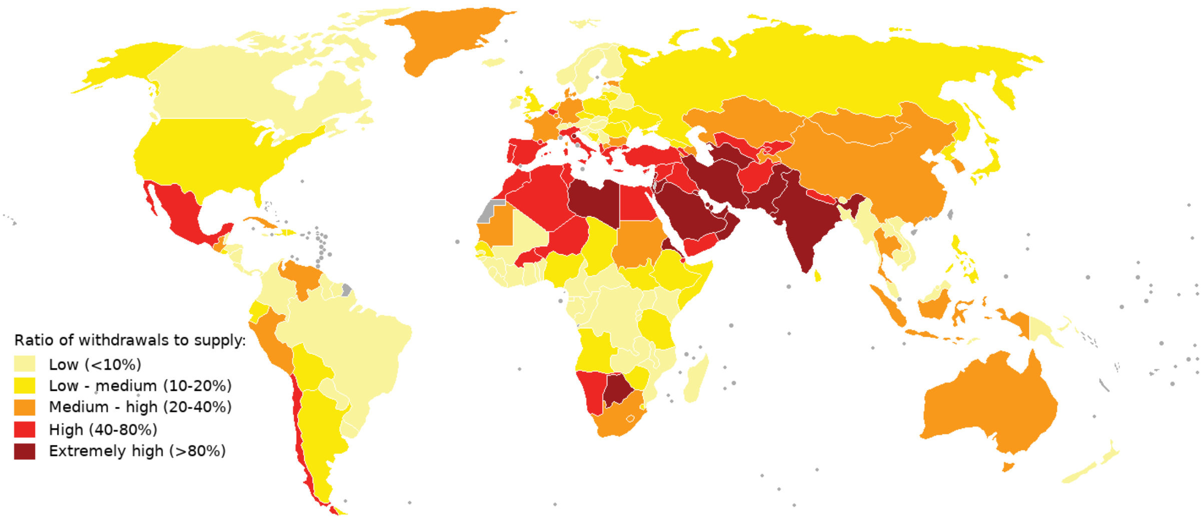


Fig.2 Water Stress Map

Case of rural areas and arid areas are the common places that the demand for water can't be fulfilled [5]. The roots of this issue because percentage of fresh water in the earth is 3% (lakes, rivers, groundwater, and others), and the rest of about 97%, is saltwater in the oceans [5]. Furthermore, nowadays, freshwater is quite limited because it's stored either in the underground or in the form of snow/ice, only 3% that can be used by humans. In addition, lakes and rivers, as the usual water source for rural areas, only contain 0.25% of the available fresh water source. Hence, the availability of freshwater for the human has become rare, and it gives a negative impact on drinking consumption and any activities that involve freshwater (e.g., irrigation and household activities). Saltwater is one of the solutions that very easy to be applicated. Saline water is mainly divided into two types, which are brackish water and seawater [1]. The difference between these saline water sources is the content of salt, which in the brackish water (1000 ppm – 25000 ppm) is lower than the seawater (>25000 ppm) [6]. As mentioned above, the amount of saltwater in the ocean is abundant, and it means seawater has been looked at as the feasible option for potable water production to solve the water-drinking issue. Desalination can become the best option to become the solution to overcome water scarcity issue due to harness abundantly saline water sources (e.g., ocean and sea). Desalination is the process that involves the separation of solute concentration (NaCl, B, and other chemical compounds) with nearly salt-free fresh water [7].

Desalination technologies are classified based on different criteria [5]–[7]. According to Youssef et al. [6], there are three major types of desalination systems which are thermally-activated systems, pressure-activated systems, and chemically-activated desalination methods. On the other hand, according to El-Dessouky et al. [7], there are two types of technologies which is desalination technologies driven by thermal energy and desalination technologies driven by mechanical/electrical energy. In Fig.3, the classification hierarchy of desalination process based on the driven technologies is shown. Those technologies are still keep developing and improving until now.

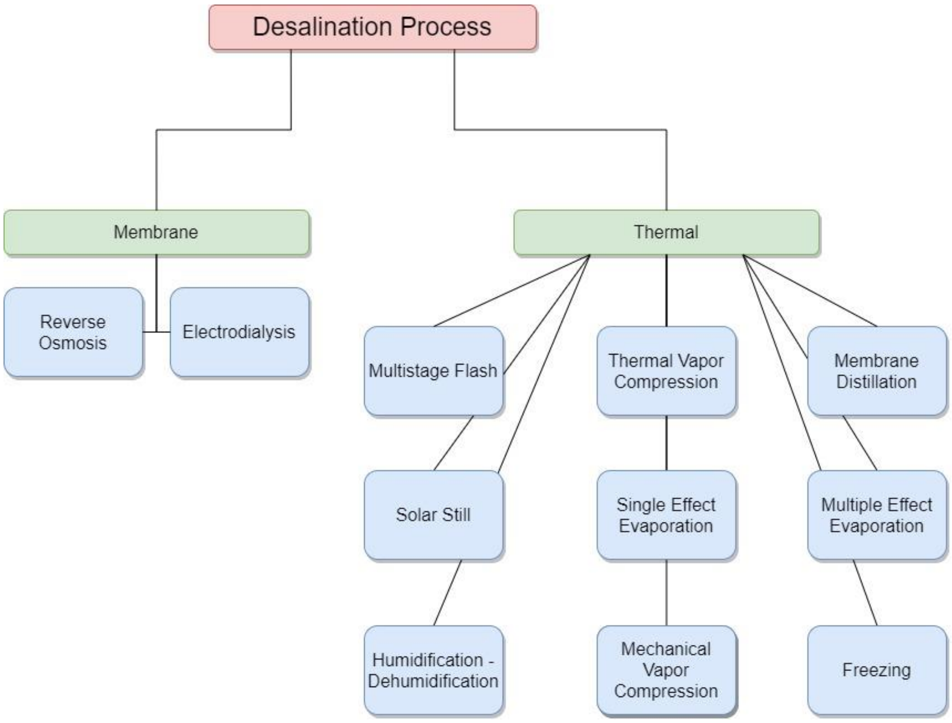


Figure 3. Classification of Desalination Technologies Based on Main Energy Form [7]

In the thermal energy-driven desalination process, there are two types of technologies [7]; the first is evaporation, followed by condensation of the water vapour. The second involves freezing, followed by melting of the formed water ice crystals. Examples of thermal energy-driven desalination process are Multistage Flash Desalination (MSF), Multiple Effect Evaporation (MEE), Single Effect Vapor Compression (SEE), Humidification-dehumidification (HDH), freeze desalination, and solar stills. Multistage Flash Desalination is the leading technologies in this category due to the most convenient for large scale application and it has been the common technologies used in arid areas like Saudi Arabia [8]. The main source of energy for thermal energy, usually from power generation units, either steam or gas turbines. However, solar energy also has become the consideration to applicate on this desalination process.

For mechanical/electrical energy-driven desalination technology, the process uses electrical energy to drive mechanical pump for passing the seawater, or brackish water through semi-permeable membranes process into freshwater permeates and highly concentrated brine solution [7]. The common technologies are Reverse Osmosis (RO) and Electrodialysis (ED). The difference between those both technologies are for RO is driven by mechanical energy, and ED is driven by electrical energy.

Reverse osmosis (RO) is a desalination process used to separate dissolved solutes from the freshwater which using pressure-driven membrane [9]. Reverse osmosis membrane is typically a semipermeable membrane, which is a membrane that allows a permeable fluids/component in the feed stream and blocks the impermeable components that have a thickness of less than 1 mm. The permeable fluids are usually called as permeate solution, and the impermeable is called as solute solution. The schematic operation of reverse osmosis is shown in Fig. 4.

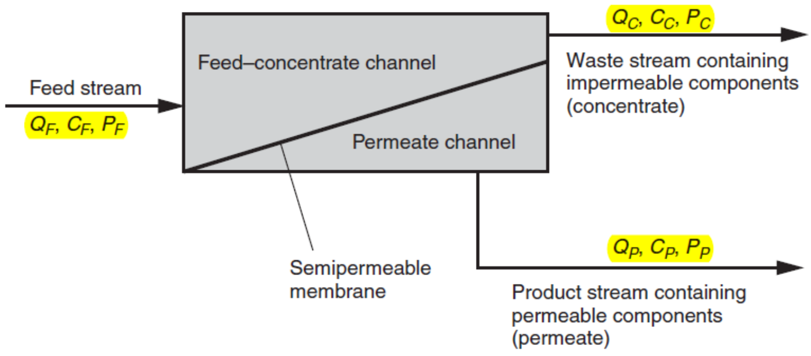


Figure 4. Schematic Operation of Reverse Osmosis [9]

Reverse osmosis has been implemented on many water treatment plants and has been used to supply drinking water in some regions [10]. About 65% of global desalination plants are based on the reverse osmosis process[1]. The reverse osmosis system/process consists of a semi-permeable membrane that allows the passage of water molecules but not the majority of dissolved salts [1], [5]. The principal work of reverse osmosis creates the pressure energy above the osmotic pressure of a solution [5]. In practical, standard pressure of the reverse osmosis plant is 50 bar - 80 bar. Reverse osmosis has two output streams which are called rejection solution and permeate solution. The rejection solution will have high salinity or contained many chemical substances and preferably, it will be recycled again to become the feed input or used for other systems, e.g., salt production [10]. On the other hand, permeate water is the product water with low salinity and can be used for human consumption. Nowadays, there are several large plants of reverse osmosis around the world that used to provide water to their territory [10]. The reverse osmosis process is capable of producing the water quality that corresponds to the WHO standard (< 500 parts per million (ppm)) and contribute to fulfilling the worldwide freshwater water demand [5]. RO system is also more flexible than other systems in the case of source water condition, location of the plant, and operational management [11].

In the whole reverse osmosis operation system, there is pre-treatment and post-treatment process [12]. Pre-treatment of reverse osmosis is used to remove the suspended particles from the saline source water and to avoid precipitation, cake formation, and scaling in the membrane of reverse osmosis (RO). Other advantages of pre-treatment are the saline source water will have lower dissolved solids and would make the fresh water product become better, which can also make the high-pressure pump consumption also lower. This would make energy-saving and cost-saving become better. Besides the retention of suspended particles, the pre-treatment process also consists of pH adjustment and antiscalant addition [9]. The purpose is the same as the filtration process, which is used to prevent precipitation and to scale on RO membrane. The post-treatment process includes the removal of dissolved gases, alkalinity, and pH adjustment [9]. In reverse osmosis, the membrane cannot remove small and uncharged molecules, particularly dissolved gases. The typical gases to be removed from the water are Hydrogen Sulfide and Carbon Dioxide. Both of those gases are harmful to human. Permeate solution has low in hardness and alkalinity; thus, it makes the solution corrosive to the equipment and piping. Alkalinity and pH adjustment are suitable processes for solving this issue, and it has been proofed as the best way to control corrosion.

However, there are two major issues of reverse osmosis [1]. The first one is the effluent of reverse osmosis can be harmful to the environment, consider the water will have greater salinity than before. Besides the effluent, the emission of greenhouse gases (GHGs) due to fossil fuel consumption (for electricity generation used to drive the RO plant/system) has an adverse effect on the environment. These two aspects are the most critical issues in sustainable freshwater supply using RO system that have to be paid attention to the design and operation of reverse osmosis plant. Secondly, the pump unit on RO plant is powered by electrical energy, and it would make high operational cost and high energy requirements [8]. With this issue, the fuel cost for RO system would high, and it also triggers the first major issue, which is the contribution to global warming (because of emitted GHG). The utility of renewable energy as becoming driving energy input can become the solution to overcome this issue, but it’s still limited to the application of large-scale system [1]. The application of reverse osmosis driven by renewable energy with the energy recovery device is the superior technology, and there is a lot of research and pilot plant of this desalination technology [13]–[15]. Currently, there are research and developments of reverse osmosis technology to overcome the major issues of RO system. Rezk et al. (2019) analyse the design of RO desalination system driven by stand-alone solar PV with battery application as energy storage [16]. In this design, the RO plant has a low energy consumption and also zero CO_2 emissions due to the advantages of a solar PV system, and it means the operational cost will be lower, and it gives environmental sustainability. Wilf and Bartels suggest methods for optimizing seawater RO system design by considering the configuration and operating parameters of the current RO plant [10]. They indicate the development of RO system from them are application of the two-pass system on RO unit, additional post-treatment process, and added pH feed water for removing boron on the pre-treatment process. Based on the experiment from Wilf et al., the improvement with the following method can decrease desalination cost, improve efficiency energy, and improve the rejection of solute. Al-Zahrani et al. carried out a thermodynamic analysis of RO desalination unit with and without energy recovery device (ERD) [17]. The analysis is used to investigate the effect of energy recovery device on RO plant, and the result shows that RO plant with energy recovery device has more energy-saving than a plant without ERD. Furthermore, RO plant with ERD is very useful for RO system performance due substitution of pressure between rejection solution that has high pressure and upcoming feed water to minimize the energy consumption of the high-pressure pump. Oh et al. (2009) developed a simulation model of RO system using the solution-diffusion model [18]. They studied the effect of recovery ratio and permeate flux on the overall efficiency of RO system with wide range of operating parameter conditions. They also studied the effect of fouling mechanism on membrane for the efficiency of RO system. Based on all those experiments and researches, it can be concluded that RO system isn't a new technology and it's always developing along the time. Furthermore, the use of renewable energy as their driving equipment can be significantly improve of RO unit e.g., solar PV-RO, wind energy-RO, and many more. In addition, reverse osmosis still being the main leading technologies for desalination system, especially if the application for large scale.

Islands, rural, and arid areas are the typical places that have water scarcity issue. Furthermore, in those areas, water transportation is very hard, and some places might not have any water storage tank. Especially in the island areas, availability of fresh water could be scarcer than in the rural and arid regions due to the limitation of fresh water access. The fresh water transportation to the island areas also needs more time and money. The most common transportation of fresh water is by ship, and it's estimated cost of about 7€/m^3 [15]. This reason also becomes the cause of high-water cost in the island area. This has a bad impact mainly on developing countries, especially in countries like Indonesia. Island areas are the most substantial area in Indonesia, and In Fig. 5, you can see the map of Indonesia which contain a lot of islands.

Figure 5. Indonesia Map [19]

The typical price of potable water at islands in Indonesia is (58€ - 74€)/m^3 [Ref.] and it's very expensive for people who lived in island areas. Thus, they usually instead drink the water directly from the sea or any water source which are unhealthy and unsafe. Furthermore, water treatment plants/desalination plants still located only in the biggest cities and also suffered from uneven distribution. Whereas, for islands situated far away for these cities, the supply of potable water becomes costly and need long duration for transportation.

According to Fig. 5, Indonesia is an islands country, and it's surrounded by sea. This characteristic can become one of the solutions to solve the water scarcity issue. The application of desalination technologies is very relatable to the conditions of this country. However, Indonesia also the highest greenhouse gas emissions in the world [20]. Thus, the selection of suitable desalination has to be carefully carried out to address the issues related to the environmental impact. Another advantage is Indonesia has the highest solar potential. The application of solar energy powered desalination system is very suitable in this country [21], [22]. Hence, the application of desalination technologies driven by the solar-powered system is the best choice for such locations. Solar driven desalination technology is still developing but has been implemented in several locations around the world [23]. In Fig. 6, categorize of desalination technology driven by solar energy is shown.

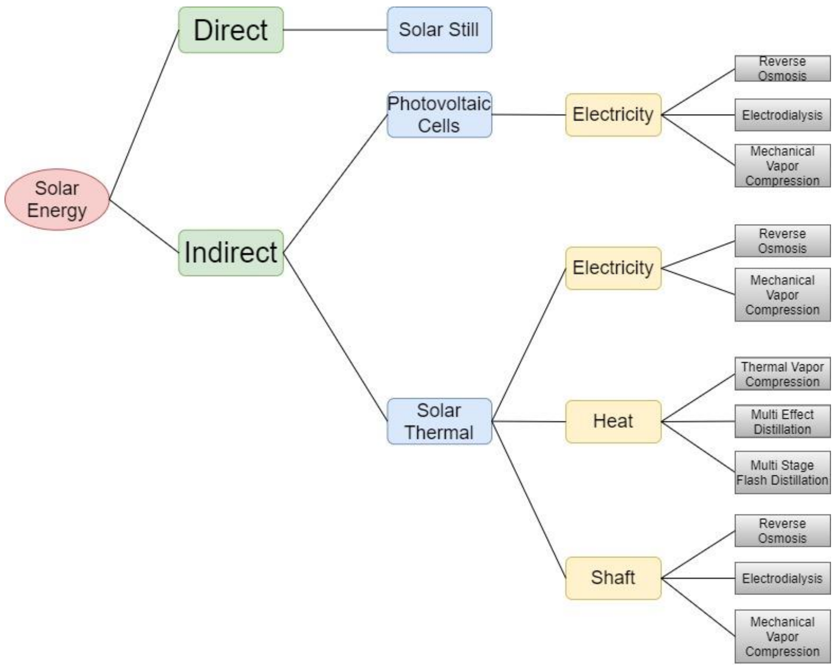


Fig 6. Classification of Desalination with Solar Energy [24]

The various types of solar technology become the main categories in this classification due to different output and result from those technologies. The kind of output form (electricity, heat, or shaft) by solar technologies also become the differentiator on this categorization. This types of desalination with solar energy already available on the pilot plant scale or still in the design process but have been published in scientific paper. In the future, the application of desalination with renewable energies would keep developing and could replace fossil fuel to become the main source of energy of desalination technologies.

1.2 Justification

The application of desalination technologies is emerging and growing over time. The necessity of freshwater becomes the main issue around the world, and desalination is the eminent solution. The market of desalination technologies are growing fast across the globe, but it's still got challenges related to the use of fossil fuels (e.g. oil and natural gas) to driven the energy-intensive desalination process, especially in the large scale application [24]. These problems include the operational cost and the negative effect of effluent. However, as stated above, there are many theoretical and experimental studies about using renewable energy sources to substitute fossil fuels for seawater desalination applications. Wind, photovoltaic, solar collectors, and biomass become a suitable replacement for fossil fuel consumption in desalination plants. Also, nuclear energy also become one of the considerations, but it has a negative public image and has several risks for the environment.

Nowadays, the research focuses on two kinds of desalination technologies, which are indirect and direct desalination using solar energy [24], which have been shown in Fig. 6. The research by Rizzuti et al. is focused on using solar energy to become the main source. Especially in rural areas or arid areas with high solar energy potential and surrounded by seawater, this kind of technology can fulfil the demand for potable water. The difference between these technologies is the solar energy on direct desalination is used to process the seawater into the nearly free-salt fresh water. On the other hand, the indirect desalination is generated by conversion solar energy into electrical/mechanical energy to become the driving energy of desalination process.

With the ability of converted solar energy into electrical energy and it could minimize electrical energy consumption generated using fossil fuel, solar energy technology is suitable to be applied for seawater desalination. There are several applications of solar energy with desalination technologies like solar PV-RO, solar PV-Electrodialysis (ED), Solar-MED and many more [1]. The most common desalination technology with renewable energy is solar PV-RO and it has been applied in many small-scale plants or pilot plants. The ability of solar PV to produce high electrical energy can be used to driving feed high pressure pump of RO system. The suitable solar energy technologies for RO unit is stand-alone photovoltaic generator because it can be supplied the electricity without electric grid [1], [11]. With using this type of solar technology, the application of solar PV-RO is simplified and can located in any rural or arid areas with high potential of solar energy. Furthermore, application of battery storage on solar PV-RO can profitable on the technical and economic aspects [1]. However, there is many limitations on battery storage to be applied on solar PV-RO especially if it's large-scale application. Although, there is a possibility to use battery storage on small scale installations like in Herold et al. built in Gran Canaria, Spain [11]. The plant is used to create potable water production of 3 m^3/d using reverse osmosis technologies and energy supplied from solar PV. The plant also studied about management and control strategy of solar PV-RO system. Rezk et al. also tried to developed and optimized stand-alone solar PV-battery system for driving reverse osmosis unit [16]. The plant is located on Al Minya (Egypt) and the calculation model used HOMER software package. The result shows that this plant show the better performance than diesel generator-RO and utility grid-RO. Furthermore, the application of solar PV-RO can reduce amount of CO_2 emissions that created by diesel generator. With all those theoretical and experiential studies about solar PV-RO, it can be concluded that this system can be one of best solution in the desalination technologies. All the issues that have been mentioned before can be overcome, especially to deal water scarcity issue around the world. However, all the limitations of this system have to be pay attention and considerate again. Application on large plant will be the target of work in the future.

For Indonesia, the fresh water demand is very high due to the vast population of the country. According to the data from the Ministry of Internal Affairs [25], the total population in Indonesia is 269 million and will keep increasing throughout the year. If we calculate the water demand based on WHO [26], which is 20 l/day per capita, Indonesia needs 5,380 million litres of fresh water per day. It is an enormous demand t and challenging to achieve if the country relies only on available natural freshwater sources. In addition, the island's conditions that have been mentioned earlier also become one of the biggest reasons to fill those demand. However, if small-scale decentralized water production technology implemented in each specific location in Indonesia, it could be contributed substantially overcome the potable water scarcity of the country. Small-scale PV-RO plant is one of the most well-known desalination technology around the world and has been implemented [11], [26], [27]. From all those papers, it can be concluded that most small desalination of PV-RO plant can produce 1 m^3/day – 20 m^3/day. Although, if water production below 1000 m^3/day, it also can be called a small desalination plant. This amount of water can become one of the solutions to solve water scarcity in the island country like Indonesia, and moreover can become the main water production.

In this research, Madura's Island becomes the selection location for the calculation and simulation data. This selection is based on the potential of solar energy and geographical condition. Furthermore, Madura's Island also has water issue from the shortage of fresh water, the necessity of clean water, and scarcity of fresh water source. In addition, the water condition on Madura also contaminated by the industrial effluent since Madura is one of the biggest iron production industry at Indonesia. This location is suitable to install the PV-RO desalination system with all those potential and backgrounds.

1.3 Objectives

The main objectives of this research are to study the possibility of application small-scale reverse osmosis desalination system driven by solar PV system for Madura's Island. The specific objectives for this research described as following:

- Investigate the energetic performance and economic viability of solar PV driven reverse osmosis (RO) operating on Madura's Island in Indonesia.
- Investigate the possibility of commercial purposes of Solar PV driven reverse osmosis (RO) plant on Madura's Island in Indonesia.
- Compare the cost of water production on Madura with water production on solar PV driven reverse osmosis (RO) plant.

1.4 Scope

There are several limitations and assumption to developing this research. Those describe in below as following:

- This research use simplified solar PV and reverse osmosis model as the intention of this research as a feasibility study.
- Writers neglected the optimization of the solar PV+RO system.
- The solar PV+RO system is a small-scale plant.
- The location of the research is Ujung Piring Village at Madura's Island

1.5 Methodological Approach

This research will be considered the following aspects:

- Conceptual and numerical modelling of PV-RO desalination system.
  In this step, simulation of solar PV system and RO desalination system are formulated. The simulation is from numerical modelling based on theoretical of solar PV technology and RO desalination technology. The results will show the potential of coupling solar PV system to driving RO desalination system.
- System performance simulation based on variation water temperature data on Madura using commercial software platforms.
  In this step, monthly data results from the simulation of the solar PV system and RO desalination are obtained. The variation data of simulation is obtained by used water temperature data on Madura for each month. The results will show the correlation of water temperature data with the performance of PV-RO desalination system.
- Techno-economic analysis of PV-RO desalination system under different parameters.
  In this method, technical performance and economic parameters of PV-RO desalination system are established. Performance indicator and economic indicator become the main parameters for this techno-economic analysis. The results will show the potential of the application of PV-RO desalination system on Madura's Island in a year.

2. System Description

2.1 PV-RO Desalination System Description

The PV-RO desalination system has many variations of design, and it's dependent on several factors that need to be considered (e.g., location and capacity). However, in most of the research studies and pilot plant designs, there are common components (e.g., inverter, energy recovery device, and booster pump). In Fig.7, the schematic diagram of the small-scale PV-RO desalination system for this research is shown.

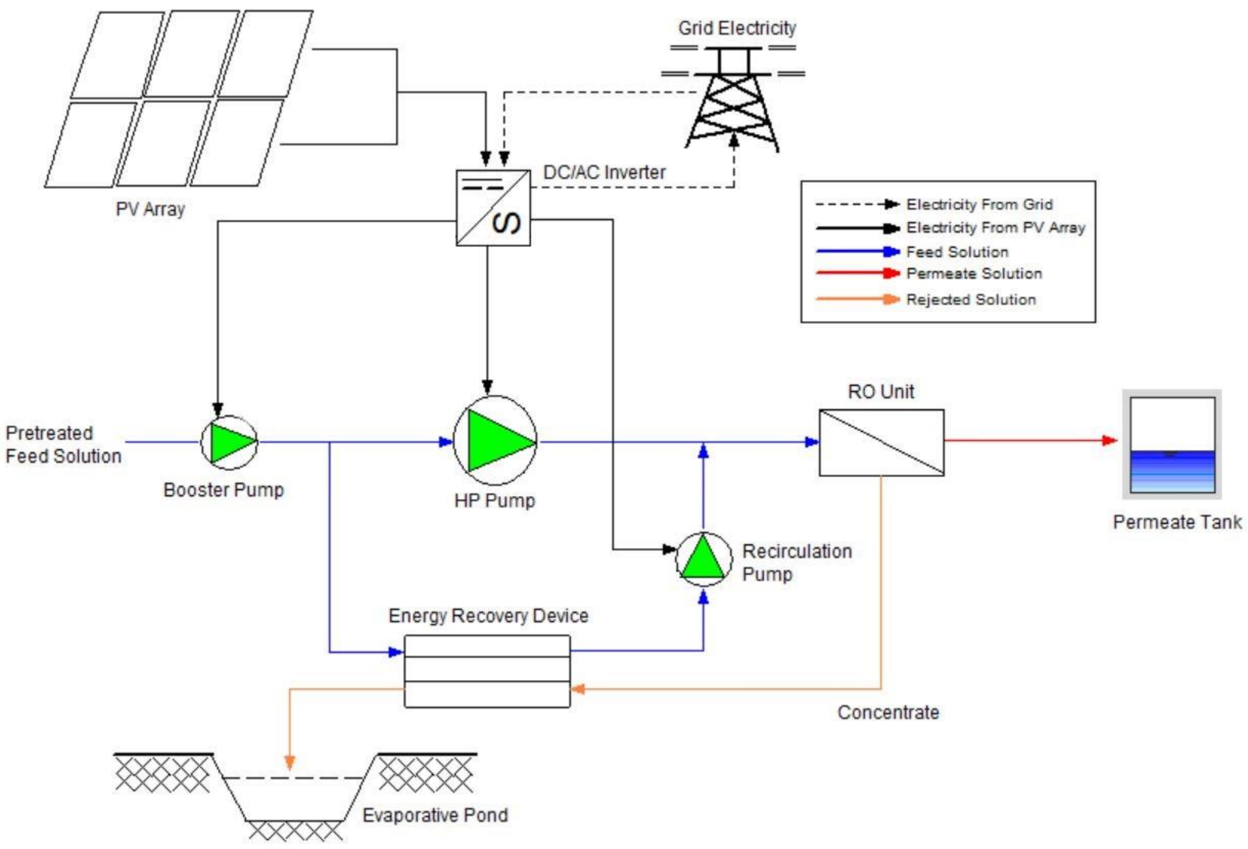


Figure 7. Schematic Diagram of PV-RO Desalination System

The PV-RO system will use renewable energy or, more precisely is solar radiation as their main source of driving energy. This system has six key components which are PV array, inverter, high-pressure pump, reverse osmosis unit, permeate tank, and energy recovery device. There are also other additional components likes evaporative pond and booster pump. This system is using a battery-less concept to minimize the investment cost of the plant and to study the effectiveness of the permeate tank as the substitute for energy storage using the battery. In Fig. 1, it can be seen the energy flows from each component and also the water type that flows in or out of the reverse osmosis system.

The electricity is delivered by PV array and the back-up electricity from the utility grid. The back-up electricity is important because the disadvantage of this system is intermittent energy; thus when the

PV array can't deliver electricity or less-delivered electricity to the pump, hence the grid system will provide the electricity to the pump. On the other hand, when the PV array has excess electricity, it will be exported to the grid system. PV array and grid electricity are connected with DC/AC inverter, connected with the AC pump.

As have been mentioned before, reverse osmosis is a simplified model; thus, the feed solution has been assumed as pre-treatment water, whereas avoid RO fouling and scaling. The feed water will enter to the high-pressure pump and deliver to RO unit. In the RO, the water will be separate into the permeate side and concentrate side. On the permeate side, the water will be contained in the water tank to be consumed by the community. On the other hand, the concentrate side will go into the energy recovery device since the concentrated brine still has high pressure.

The concentrated brine will enter the energy recovery device (pressure exchanger device), and on the opposite side, there also input from feed water. The high-pressure concentrate water will transfer its energy into the low-pressure feed water. Hence, the feed water will gain more energy, and it will enter into the booster pump to meet the applied pressure on the reverse osmosis system. The rejected solution that exits from the energy recovery device will go into the evaporative pond, as has been the common technologies on all solar PV driven reverse osmosis plant.

2.2 System Components

There aren't any standard components of PV-RO desalination system, but from all studies in the literature and pilot plants around the world, it can be concluded that there are several key components to be applied in the design of any PV-RO desalination system [28]. In addition, in the study of this desalination system (shown in Fig. 7), there are also other components that need to be considered. The following components that are necessary for the design approaches of PV-RO desalination system are:

- Solar PV

  As has been mentioned in above, the variations of the solar powered system coupled with desalination system are explained. Solar PV is the leading technologies for applied in the desalination system, especially reverse osmosis technology [29]. The function of solar PV is to deliver the electricity into the high-pressure pump unit for driving seawater or brackish water through the semi-permeable membrane. Mono-crystalline and multi-crystalline silicon modules can be used to generate power to RO unit. The important factor is module orientation and radiation intensity on the location. The application of a tracking system or adjustable axes in the solar PV module can increase the overall performance of the modules and also increase the overall performance of the desalination plant.

  The validation of tracking system utility on solar PV module to increase electrical power output from solar PV and permeate flow rate from RO unit has been available [28]. Application of maximum power point tracker (MPPT) is obligatory to applied on solar PV, especially in the RO desalination system. This optimizer is used to maintain system operation that achieves maximum power while ensuring efficiency under conditions of low irradiance.

In this thesis, solar PV system will become main energy source for driving pumps on RO system. The output power of solar PV is DC power which will be converted by AC/DC inverter. If solar PV system can't or not sufficiently deliver electrical energy delivered to RO system, grid will become the energy source. Therefore, in this thesis, solar PV system will be designed to have maximized electrical energy production to decrease the utility of electrical energy from grid.

- AC/DC Inverter

  In the several RO desalination plant, AC induction motor is the selection for their high-pressure pump. The function inverter is to transform the DC current generated by PV modules stored in the batteries or from grid electricity. Moreover, the inverter is also used to delivered electricity to the grid in case if the system decided to sell the electricity. However, there are other causes for not use AC/DC inverter in the PV-RO desalination system, which is the application of DC motor for their high-pressure pump [29], [30]. The application of DC motor will be more explained in the high-pressure pump section. The inverter also can be applied as a regulator to control the electrical load to the high-pressure pump. The application of AC/DC inverter also has several failures and will impact the desalination system [28]. The first is inverter usually has overheating during plant operation, and it stops the electricity input to the high-pressure pump and stops the reverse osmosis operation. The second is overloading at the motor pumps when the single RO unit has several motor pumps and no soft-start features are installed.

  As explained before, the inverter in this design will become the converter of DC power to AC power. This converter is necessary since all the pumps used in the RO system are AC pumps. On the conversion process, there will be power losses and it will become one of consideration in this design. This component also used to transfer excess electrical energy from solar PV system to grid system or called selling electrical energy. Installation of inverter for solar PV system will create the limitation of the configuration of PV array in the sense of voltage and current. Therefore, the configuration of PV array to achieve maximum electrical energy production becomes one of the intentions in this thesis.

- Pumps

  As a corresponding to the theory, positive displacement pumps are used for the high-pressure pump of RO desalination system due to their high energy efficiency – concerning the centrifugal pumps – at low flows [28]. The common pump that used of high-pressure pump is rotary displacements pumps [13], [31] and reciprocating pumps [32], [33]. Pump motors can power by direct current (DC) or alternating current (AC). If the PV-RO desalination system uses AC motor, thus inverter has to be applied. On the other hand, if the DC motor is the choice, the inverter application can be eliminated. However, the application of DC motors involves a higher initial investment. Besides the expensive cost, DC motors also don't experience energy losses by inverters, and it makes the PV-RO desalination plants can obtain higher energy efficiencies.

In this PV-RO desalination system design, there are three pumps, and they are AC pumps. These three pumps are high-pressure feed pump, feed booster pump, and recirculation pump as shown in Fig.7. Feed high-pressure pump will deliver feed solution into RO unit and increase the feed pressure to overcome osmotic pressure before entered membrane. The feed booster pump will deliver the feed solution into the pressure exchanger device for substitutes the pressure from rejected solution. The latter pump is a recirculation pump is to slightly increase the pressure of feed solution that already has high-pressure from pressure exchanger device.

- Reverse Osmosis

For the PV-RO desalination systems, spiral-wound and thin-film composite RO membranes are the typical selection. In the same research or scientific papers, reverse osmosis configuration is a single stage and single pass to simplified the calculation and process operation [18]. Definition of single-pass and single-stage is the membranes are organized in series within one or more pressure vessels in a parallel arrangement. Configurations are important parameters for the reverse osmosis unit, and it can also be methods to optimize energy efficiencies [26]. The selection of reverse osmosis also has to consider the ability of salt rejection and recovery rate. Both parameters can affect energy efficiencies and pressures of reverse osmosis. According to Ghermandi et al. [28], if brackish water is the source water for desalination flow input, the technology of nanofiltration is the best choice due to cost-effective and can be alternative substitutes for reverse osmosis technology. Nanofiltration has lower operating pressures and energy requirements.

For the performance of reverse osmosis, there are several parameters that have to be counted [18]. According to El-Dessouky et al. [7], the performance parameters of reverse osmosis are:

a. Mass Balances and Salt Balances
b. Osmotic Pressure
c. Water Transport
d. Salt Transport
e. Concentration Polarization
f. Salt Rejection
g. Recovery Rate

It has to be remembered that all those parameters are related to the flow rate, concentration of the solution, and pressure. Nowadays, the reverse osmosis element also has cost variation, which is from $250 - $1000 [26]. However, the maintenance cost of reverse osmosis still become the problem due to the replacement of semi-permeable membrane, which depends on manufacturers. The lifespan of RO without membrane replacement is 20 years, and its relatively long time.

In this design, there are five RO element that installs on RO unit. The configuration of RO element in this RO unit is in series. Permeate solution each of RO element will go into the permeate tank directly. The rejected solution from the first RO element will become the feed solution for the second RO element, and the process will remain the same until the last RO element. The rejected solution from the previous RO element will go to the pressure exchanger device and finally into the evaporative pond.

- Energy Recovery Device

  Utility of energy recovery device (ERD) on reverse osmosis system become one of the important tools to be applied. There are several technologies of ERD likes Clark Pumps, Hydraulic Motors, Energy Recovery Pumps, and Pressure Exchanger [28]. The best method to determine the best energy recovery device is to look at the specific design of the desalination system and correlate with it. It has to be attention that not all energy recovery device types can be applicated to the desalination system. Reverse osmosis is one of the desalination technology that can be coupled with a variant of the energy recovery device [34], [35].

  The energy recovery device used in this PV-RO desalination system design is a pressure exchanger (PX) device. This component will swap pressure from a high-pressure rejected solution to low-pressure feed solution. This component is used to decrease work consumption from the high-pressure pump in this PV-RO desalination system. The rejected solution that has the lowest pressure (output of PX device) will goes into the evaporative pond to be treated.

- Pre-treatment Unit

  As have been mentioned in the introduction, the pre-treatment unit of reverse osmosis is the important process to avoid scaling and precipitation on RO membrane. The pre-treatment can either by filtration or using a chemical substance. The filtration process can be called as conventional RO pre-treatment [28]. This pre-treatment process is commonly implemented on RO plant. The pre-treatment filter has a pore size of 5μm, and it leads to a coarser filter with a pore size of 20 μm – 25 μm or even larger. This filtration process also removes chlorine substance and can damage the RO membranes. The filtration process also blockage biofouling due to bacterial or other microorganisms [12]. The pre-treatment unit's new technology is ultrafiltration (UF) pre-treatment, and currently, it’s eminent technology [36]. The ability of ultrafiltration pre-treatment can remove significantly number of microorganisms and eliminates the need for membrane disinfection. Furthermore, UF pre-treatment also may reduce RO maintenance likes membrane cleaning or membrane replacement. The chemical pre-treatment process usually uses antiscalant to reduce the possibility of membrane scaling. However, there is other alternative method without use chemical substances which is using the RO membrane with low recovery rates. This method can prolong membrane lifespan and avoid the scaling.

In this thesis, pre-treatment unit doesn't count on performance analysis but there is consideration on economic analysis. This PV-RO desalination system design assume has treated feed solution. Therefore, fouling and precipitation can be avoided. In economic analysis, chemical application is become one of countable parameter to illustrate total operational cost of this desalination system design.

To support all the components that have been mentioned earlier, there are other several tools that can be add into the solar PV-RO desalination system. All these components have been used by many researchers or used in the pilot plans. It is not necessarily important to be applied on PV-RO desalination system but it gives a better impact to the system. The following additional components of PV-RO desalination system are:

- Battery

  Battery is one of the energies saving components that usually used for PV solar system. The intermittent energy that created by PV solar system can become the biggest issue on the application. For the coupled to reverse osmosis desalination system, battery has been usually used to maintain the operation. The utility of battery can prolong the work operation and achieved the desired capacity of system. However, battery has a quite drawback likes the expensive of instalment cost and the tricky of maintenance. Battery has a short lifetime and it will take a lot of cash to replace it. Thus, installation of battery for the PV-RO desalination system has many considerations, especially on the location characteristics. Nowadays, there are experiments or research papers for studied the substitution of energy saving component for PV-RO desalination system.

  Battery isn't applied for this desalination system design due to drawback of this component. Moreover, in this desalination plant, the electricity also can be supported by grid which makes the system doesn't require energy saving component. Therefore, installation battery can be avoided for this case.

- Grid Electricity

  Grid electricity also can become one of the electricity sources for overcome the intermittent energy from PV solar system. The electricity supply from grid can fill the incapability of solar PV in the night of when the system can't fill the electricity demand. Furthermore, grid electricity also can become the income for the PV-RO desalination system. If there is any excess electricity from PV solar system, it can be directly sold to the grid depend on the rules of the country. However, connection of solar PV system with grid electricity also has the limitation likes the grid has to be near with the solar PV system.

Grid electricity in this design is become the backup system for supply electrical energy. Since solar PV system can't fully work continuously, this system is become one of requirement for desalination plant. In Madura's Island, utility electricity from grid isn't difficult and would become more effective than battery installation.

- Evaporative Pond

  Evaporative pond is the leading component that controlling the brine output from desalination system. This pond is usually to evaporate the saline water and leaves the salt behind. Furthermore, this component uses solar energy from the sun for the evaporation process. However, in some cases, the additional heat component is used for specific purposes. To avoid the harmful effect of brine solution into the environment, evaporative pond gives the best solution which collect the saline water into one large area. In some cases, the salt that leaves on evaporative pond become the additional product of desalination system. Thus, the efficiency and income cost can increase.

  Since brine from rejected solution will harmful the environment, this desalination system design has brine treatment which is installation of evaporative pond. High saline water at rejected solution would be collected in this evaporative pond and left to evaporate. This component only uses solar energy from the sun and doesn't use any additional heat source.

- Water Tank

  Water tank is the one of substitution of battery utilization in desalination system. With the disadvantages of battery, water tank can become the energy saving of desalination system in different way. The water tank can save the fresh water production from desalination system and can erase the requirement of 24 hours work on desalination system. On the case PV-RO desalination system, it can work on daylight time and harness the water production when the solar radiation in the highest position. Water tank also has lowest investment cost and doesn't need much maintenance process. However, this advantage only works on small scale desalination system which the water capacity isn't very high. In addition, this application also has to consider the purpose of desalination system and also the location.

  Water tank in this PV-RO desalination system design is used to become replacement of energy saving component. If electrical energy can't be supplied from solar PV system or grid plant, this desalination plant still has collected water to supply for community. Water tank in this plant have capacity to contained more or less three-month water production (900 m^3). Therefore, this component can become saving component in the form of water production.

3. Methodology

In this techno-economic analysis of solar-powered small-scale desalination system based on the Madura's Island (Indonesia) climate and seawater properties, numerical modelling and simulation were applied. The numerical modelling is used to obtain the RO desalination system performance using Engineering Equation Solver (EES) software [37]. The PV system electrical power production was simulated in a dynamic modelling environment using the TRNSYS software [38]. Furthermore, the economic analysis of the PV-RO system was carried out by estimating the capital and operational expenditures of the system. In Fig. 8, flow diagram of methodology is shown.

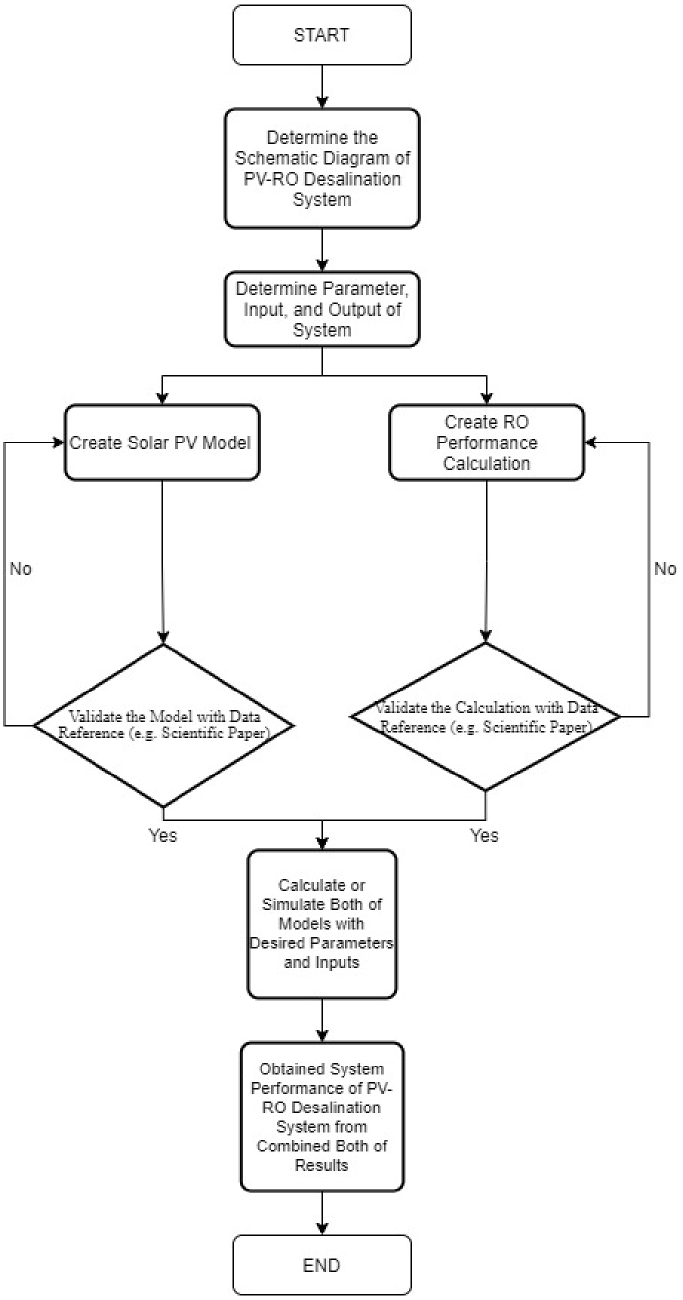


Figure 8. Methodology Diagram

In this chapter, the modelling and simulation approaches that are followed are described in detail. The performance indicator/parameters for the PV-RO desalination system performance are also provided. will explained. Furthermore, the model validation of the RO and PV subsystems are carried out using data available in the literature. Finally, the input parameters data used in the system performance simulation are described and provided.

3.1. Model Description

In this techno-economic analysis, there are 2 different simulation models that have been formulated. As have been mentioned before, the simulation model is for the reverse osmosis system and solar PV system. The software programs for both of system also different and it would be explained in each part of section. In addition, all equations for constructed this simulation model also shown and explained in this section.

3.1.1. Reverse Osmosis (RO) System

The calculation of reverse osmosis performance in this research is used Engineering Equation Software (EES). The input of this calculation is from manufacturer's data, seawater condition on Madura's Island, and assumption to simplified the simulation model. Some of the input parameters will be used to obtained characteristics of seawater (e.g., viscosity and density) by using EES input functions [37]. The equations for formulated the simulation are from the scientific papers ([18], [26]).

The calculation of reverse osmosis model is started from obtaining the manufacturer specification parameters likes solvent permeability and solute permeability. Both of parameters will be used to calculate reverse osmosis performance with the specified input parameters. In Fig. 9, flow diagram of reverse osmosis calculation is shown.

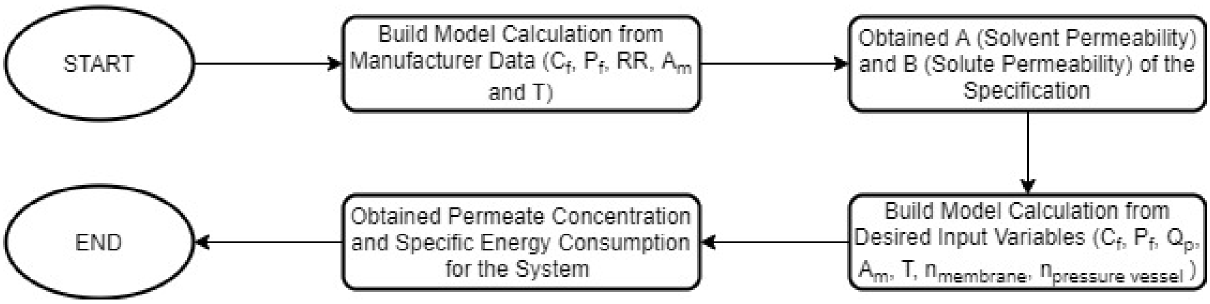


Figure 9. Flow Diagram of RO System Calculation

On developing this simulation model, several assumptions that have been made. Those assumptions divided into two categories. First is assumptions for mass transfer through the membrane and assumptions for hydrodynamics and the geometry of the RO module. Hence, assumptions related to the mass transfer via the membrane are as follows:

- The transport of water through the membrane is used Darcy's law.
- Osmotic pressure is proportional to the salt concentration.
- NaCl is only solute system that considered.
- Thin film theory is used for calculating concentration polarization effect.
- The permeate water from each element will directly mixed and goes into permeate tank.
- Fluid properties is assumed constant during filtration process.
- Fouling on RO membrane is neglected.

For the second categories, assumptions of hydrodynamics and the geometry of the RO module are described as follows:

- RO membrane module is made up of flat channels with spacers.
- Curvature effect of the RO element is neglected.
- Pressure on permeate side is 1 atm on atmospheric pressure condition.
- Axial concentrate velocity and tangential permeate velocity is neglected.

In Fig. 10, the schematic diagram of the RO system is shown. The components of the RO system (Fig. 10) selection are based on the details that have been explained in Chapter 2. In addition, this components selection and configuration is according the literature review on the simulation and pilot scale study of such type of systems ([15], [26], [29]).

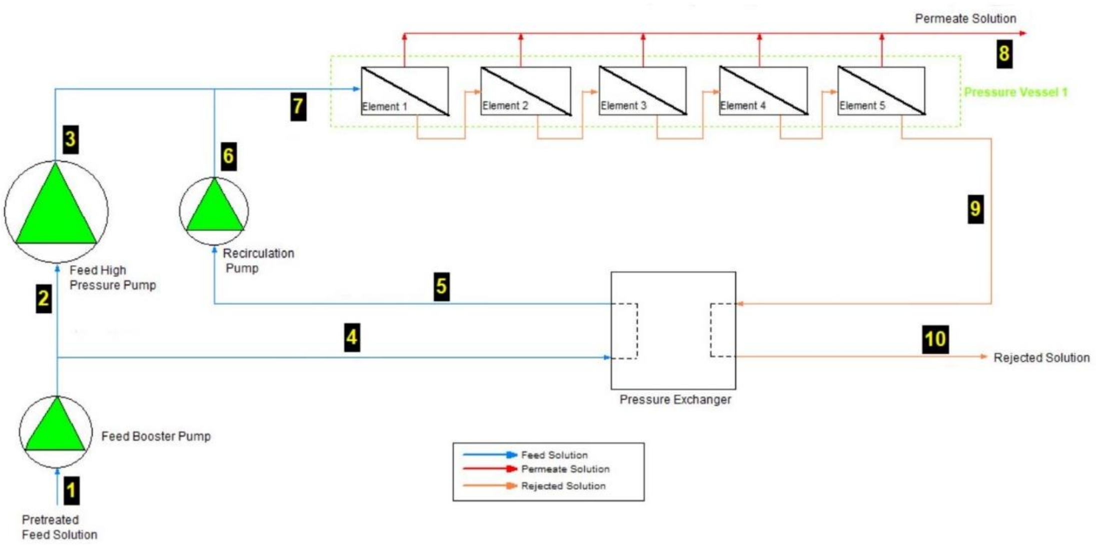


Figure 10. Reverse Osmosis System Schematic Diagram

As have been shown in chapter 2, there are several performance parameters of reverse osmosis technology system. The parameters are indicated the solution concentration, pressure, and volumetric flow rate of each stage on a single element of reverse osmosis. Furthermore, the parameters are also showing the recovery ratio and rejection rate abilities from a single element. The solution concentration and volumetric flow rate of each stage can be calculated by using the mass balances and salt balances of a single membrane. The equation as following:

$$\dot{Q}_f = \dot{Q}_p + \dot{Q}_r \tag{3.1}$$

$$\dot{Q}_f \times C_f = \dot{Q}_p \times C_p + \dot{Q}_r \times C_r \tag{3.2}$$

where $\dot{Q}_f$ is volumetric feed flow rate, C_f is feed solution concentration, $\dot{Q}_p$ is volumetric permeate flow rate, C_p is permeate solution concentration, $\dot{Q}_r$ is volumetric rejected flow rate, C_r is rejected solution concentration.

This equation will be solved or needed recovery rate and rejection rate equations. The recovery rate is correlated with the volumetric flow rate and the rejection rate is correlated with the salt concentration. The calculation is considered the states on permeate solution and feed solution. For the recovery rate (RR) equation as follows:

$$RR = \left(\frac{\dot{Q}_p}{\dot{Q}_f}\right) \times 100\% \tag{3.3}$$

where the rejection rate (Rej) expressed as follows:

$$Rej = \left(1 - \frac{C_p}{C_f}\right) \times 100\% \tag{3.4}$$

With implementing those equations, volumetric flow rate and salt concentration for a single element of reverse osmosis can be obtained.

The next parameter that has to be calculated for the performance analysis is osmotic pressure. As like the name of the technologies, reverse osmosis is the process that opposite with the osmotic law. The driving force that applied on this technology has to be surpass the osmotic pressure of saline water. The equation to determine osmotic pressure (π) is shown in following expression [9]:

$$\pi = \frac{-RT}{V_b} \ln X_w \tag{3.5}$$

where R is universal gas constant (8.314 J/K.mol), T is water temperature, V_b is molar volume of pure water (L/mol), and X_W is mole fraction of water (mol/mol)

Differential osmotic pressure ($\Delta\pi$) could be expressed by Van't Hoff's law as following [26]:

$$\Delta\pi = i(C_m - C_p)RT \tag{3.6}$$

where i is number of ions, C_m is solute concentration near membrane surface and C_p is solute concentration at permeate solution.

It should be kept in mind that the osmotic pressure is different at every each of saline water. It would depend on the salinity and other solutes on the water. Higher salinity and solute of those water, the osmotic pressure also become higher. In those cases, the feed water pressure will be higher and require more energy. In the modelling, the initial guess feed water pressure of a single membrane is equal or slightly higher than osmotic pressure of seawater. This guess will variate until the maximum limitation of operating pressure on membrane module specification.

The next performance parameter of reverse osmosis is water flux/solvent flux across the membrane. This parameter is defined the rate of water solution that pass through a semipermeable membrane [7]. The rate of water solution describes as solvent flux and it relates to the water permeability coefficient. The equation of water flux (J) as following [18]:

$$J = L_v(TMP - \Delta\pi) \tag{3.7}$$

where L_V is solvent permeability coefficient and TMP is transmembrane pressure.

This equation can be simplified as follows [26]:

$$J = L_v \times P_{eff} \tag{3.8}$$

where P_{eff} is effective pressure (bar) that obtained from subtraction between TMP and differential osmotic pressure ($\Delta\pi$)

Transmembrane pressure is calculated from pressure at feed solution (P_f), rejected solution (P_r), and permeate solution (P_p). The equation can be expressed as follows:

$$TMP = 0.5(P_f + P_r) - P_p \tag{3.9}$$

where pressure of permeate can be assumed as atmospheric condition (P_p = 1 atm = 1,01325 bar).

Solvent permeability coefficient is dependence on the specification of membrane manufacturer and it different for each type of membrane. This coefficient also depends on temperature of seawater and dynamic viscosity of seawater. This value is rarely shown on catalogue of membrane module but it can be obtained from scientific paper or any trustworthy source [18], [26]. However, those value isn't represented the seawater condition on every location. Thus, if the membrane module is same, the value of solvent permeability coefficient on specific location (L_v (T)) can be obtained according to Poiseuille's Law as follows [26]:

$$L_v(T) = L_v(T_{ref}) \times \frac{\mu(T_{ref})}{\mu(T)} \tag{3.10}$$

where L_v (T_{ref}) is solvent permeability coefficient on reference, $\mu(T_{ref})$ is dynamic viscosity from reference source, and $\mu(T)$ is dynamic viscosity of desired seawater condition. In this research, reference temperature is 20ºC and L_v (T_{ref}) is 1.63 $^{L}/_{h.\,bar.\,m^2}$ which obtained from Monnot et al. paper [26].

Pressure on rejection or concentrate stream can obtained with correlation of pressure drop in an element. The pressure drop inside an RO element can be calculated using Darcy's law equation. The equation of calculated pressure on rejection stream (P_r) as follows:

$$P_r = P_f - \Delta P \tag{3.11}$$

where P_f is feed pressure and ΔP is pressure drop. The latter variable can be described with Darcy's law equation. This equation is correlated with the hydrodynamic and geometric parameters [26]. The equation are as follows:

$$\Delta P = \left(f\,\frac{u^2}{2 \times d_h}\right)L \tag{3.12}$$

where f is Darcy friction factor for pressure drop, u is axial velocity in feed channel, d_h is hydraulic diameter, and L is length of the membrane.

The Darcy friction factor can be calculated with Reynold number (Re) and geometric spacer parameter (G). The equation can be expressed as follows:

$$f = \left(\frac{1493}{Re} + 6.60\right)G^{1.19} \tag{3.13}$$

The next parameter that necessary to calculated is solute flux. The definition of this parameter is the driving force of solute through RO membrane [7]. Actually, solute flux describes total of solute components on seawater but for this research it's only NaCl. Moreover, solute flux also correlated with permeate concentration and water flux due to relation of all these parameters at separation process of RO membrane [7]. Thus, solute flux (J_s) can be described as follows:

$$J_s = J \times C_p \tag{3.14}$$

This equation can rewrite and considerate solute permeability coefficient (L_s) and concentration near the membrane on the equation [26]. Hence, the solute flux can be expressed as follows:

$$J_s = L_s(C_m - C_p) \tag{3.15}$$

As like the solvent permeability coefficient (L_v), this solute permeability coefficient is also depending on manufacturer specification and seawater temperature. However, as like in solvent permeability coefficient, this value is rarely shown on catalogue but it can be found on the scientific paper or any trustworthy source. The equation for calculated this coefficient is different from solvent permeability coefficient because it would use the constant parameter from specified membrane [26]. This constant parameter equation (B) is shown at following equation:

$$B = -\frac{E_B}{R} \tag{3.16}$$

where E_B is energy activation and R is universal gas constant. For this research the value of B is 2290 K^{-1} which obtained from CSM Pro software [26].

In addition, with using this constant value, Arrhenius law analogy equation can be used [26]. This equation is used reference solvent permeability coefficient from same RO element but different seawater temperature value. This equation only works for same RO element and only for CSM product. The equation of solvent permeability coefficient (L_s) for this research as follows:

$$L_s(T) = L_{s,o} \times exp\left(\frac{B}{T}\right) \tag{3.17}$$

where L_s (T) is the solute permeability coefficient at specified seawater temperature, $L_{s,o}$ is solute permeability coefficient from same RO element product at difference seawater temperature (reference value), and T is specified seawater temperature. In this research, specified seawater temperature is 20°C and L_s (T) is $2.8 \times 10^{-8}\, {}^{m}/_{s}$ which obtained from Monnot et al. paper [26].

Next parameter is concentration polarization. concentration polarization is correlated with mass transfer coefficient. The equation of concentration polarization can be seen at below:

$$J = k\ ln\frac{C_m - C_p}{C_f - C_p} \tag{3.18}$$

Mass transfer coefficient (k) usually obtained by use empirical equations and it always consider as constant for a given fluid with dependence on fluid velocity. Mass transfer coefficient is also important variable to be input on concentration polarization [26]. The mass transfer coefficient is correlated with the Sherwood number (Sh), Reynold number (Re), and Schmidt number (Sc) [39]. The equation of mass transfer coefficient can be shown at following expression:

$$k = \frac{Sh \times D}{d_h} \tag{3.19}$$

where the Sherwood number (Sh) is expressed as [26]:

$$Sh = (-41.0G^2 + 22.9G - 2.52)\left(\left(\frac{Re}{0.71}\right)^{0.65} - 1.36\right)Sc^{\frac{1}{3}} \tag{3.20}$$

For the Reynold number (Re) and Schmidt number (Sc), the equations can be expressed as following:

$$Re = \frac{\rho_{SW} \times u \times d_h}{\mu} \tag{3.21}$$

$$Sc = \frac{v}{D} \tag{3.22}$$

where u is axial velocity in feed channel (m/s), ρ_{SW} is seawater density, d_h is hydraulic diameter, v is kinematic viscosity, μ is dynamic viscosity, D is diffusivity coefficient, and G is geometric spacer parameter (-). Both those variables are calculated from geometric parameter of reverse osmosis specification [26].

Besides the performance parameters of reverse osmosis calculation, there are also calculation about hydrodynamics and module geometries of a reverse osmosis element. These variables are necessary to obtained for the mass transfer coefficient and pressure drop equation as have been mentioned before. These variables are geometric spacer parameter, hydraulic diameter, and axial velocity in feed channel. Equation for geometric spacer parameter is expressed as follows:

$$G = \frac{h_b}{sbf} \tag{3.23}$$

where h_b is thickness of the spacer and sbf is space between strands.

For hydraulic diameter (d_h) can be expressed as following:

$$d_h = 4\frac{w \times h_b}{2(w + h_b)} \tag{3.24}$$

where w is width of the RO membrane and can be calculated from membrane area ($A_{membrane}$) as follows:

$$w = \frac{A_{membrane}}{L} \tag{3.25}$$

where L is length of the active membrane surface.

The last parameter is axial velocity in feed channel and it can be expressed as following:

$$u = \frac{\dot{Q}_f}{w \times h_b} \tag{3.26}$$

In Eq. 3.22 – Eq. 3.24 is depending on specification of RO element. Every product of RO element has different values for all those parameters. Thus, in this research, CSM product catalogue is used to described and obtained followed parameters [40], [41].

3.1.2 Solar PV System Simulation Model

The modelling of the solar photovoltaic system in this thesis is by using the TRNSYS software. The weather data for Madura's Island is used TMY file data. The solar PV components data is obtained from manufacture's catalogue data.

On the development of this simulation model, there are several assumptions that have been made. This assumption is to simplify the actual physical phenomena in the modelling process of solar PV system with consider to obtain maximum electricity energy production. The assumptions are as following:

- Negligible irradiance losses that created by soiling.
- Negligible DC losses (module mismatch, diodes and connections, DC wiring, and many more).
- The solar PV module is facing the equator line and the tilt is equal to the latitude of location.
- Solar PV performance only depend on the specification of module and the environmental condition.
- Solar PV system will also be supported by grid electricity when the operation isn't running or the system can't fulfil the demand

In Fig. 11, the schematic layout of the Solar PV TRNSYS model is shown. This model intends is to obtained the ambient temperature, solar radiation, electrical energy production from solar PV panels (DC Power), and electrical energy production output of the inverter (AC Power). The dynamic simulation is carried out in hourly and monthly basis. Besides, in this simulation battery or any other energy storage components are not used to obtain a low-cost solar PV system. Instead, the produced water is stored supposing that the water storage is economical than electrical energy storage.

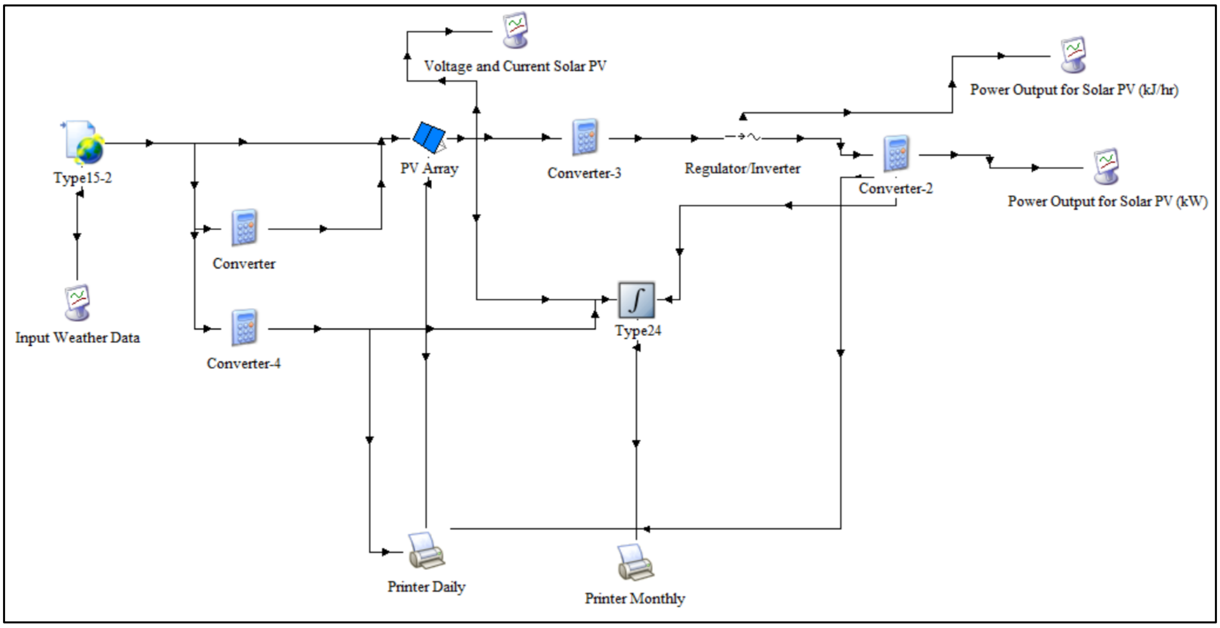


Figure 11. TRNSYS Simulation Schematic Layout of the PV System

The TRNSYS types selected for the modelling of the components of the PV system are listed in Table 1. These components selection based on simplification of solar PV system in this thesis but they are commonly used for the solar PV system performance simulation and the parameter or input for each component is refer to all assumptions that have been made in above. Moreover, in this simulation there are two kind of output which is in excel file (printer component) and online chart file (Online plotter component).

Table 1. Selected TRNSYS Component for Solar PV System Simulation

Component Name	**Number of Type**
Weather Data	Type 15-3
Solar PV Module	Type 94a
Inverter	Type 48
Integrator	Type 24
Printer	Type 25

The weather data for this simulation is TMY component data reader. The weather data that have been chosen is weather data at Bangkalan, Madura. This is the biggest district in Madura and the chosen location for this research. The weather data is obtained from Photovoltaic Geographical Information System (PVGIS) website from European Commission [42]. Slope of surface and azimuth of surface are 0^{o} and -7.03^{o}, respectively. The values obtained from the assumptions in above.

The component type chosen for the PV modules electrical simulation is the 4-parameters model available for crystalline PV modules (i.e., monocrystalline or polycrystalline PV module). In Fig.12, the four-parameter equivalent circuit is shown. The parameters are: module photocurrent and diode reverse saturation current at reference conditions ($I_{L,ref,}$ and $I_{o,ref}$, respectively), empirical PV curve-fitting parameter (ɣ), and module series resistance (R_s. These parameters are calculated using the selected PV model manufacturer' catalogue data.

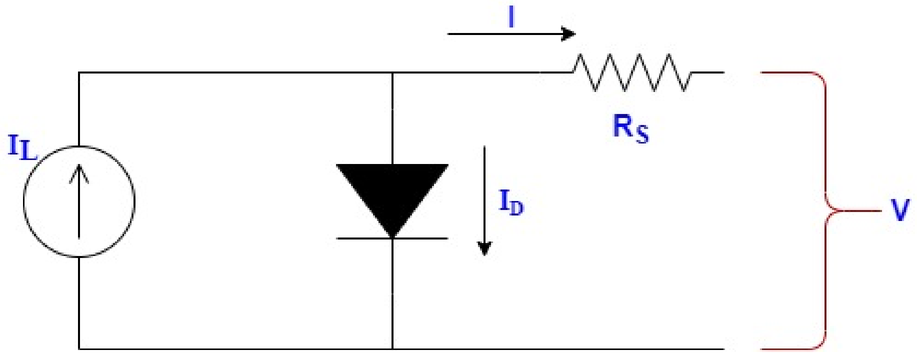


Figure 12. Equivalent Circuit of the Four-Parameter Mode (Type 94a)

In this solar PV type, the current-voltage equation of circuit is shown in following equation:

$$I = I_L - I_O\left[exp\left(\frac{q}{\gamma \times K \times T_c}(V + I \times R_s) - 1\right)\right] \tag{3.27}$$

where R_s and γ are constant.

From the equation in above, it can be seen that it gives the current implicitly as a function of voltage. The photocurrent (I_L) is affected by incident radiation and it can be calculated with following equation:

$$I_L = I_{L,ref} \times \frac{G_T}{G_{T,ref}} \tag{3.28}$$

where the reference insolation ($G_{T,ref}$) is given 1000 W/m^2 and it can be changed on the parameter section.

For the diode reverse saturation current (I_o) is affected by temperature and it can be calculated with following equation:

$$\frac{I_O}{I_{O,ref}} = \left(\frac{T_C}{T_{C,ref}}\right)^3 \tag{3.29}$$

Those four variables can't determine on a physical measurement. This component generates IV characteristics of a PV panel from the insolation and temperature data. It would make the PV model dependence on environmental conditions to generate IV curve at each timestep. The current at maximum power (I_{mp}) and voltage at maximum power (V_{mp}) are obtained from the iterative search routine and it results in maximum power along the IV curve. Those variables that used to calculated the maximum electrical power output from the PV module.

The inverter component/type that chosen for the modelling in this study is type 48a. This model applied the mode "0" which the meaning is the system doesn't applied battery (electricity energy saving component). This component also can become regulator for the solar PV array and inverter connection. On TRNSYS, this component only considers the efficiency of inverter/regulator to become the simulation parameter. The efficiency will determine the amount of AC power that can created by this solar PV system. The value of efficiency is obtained from manufacturer's catalogue specification and it's important to choose the inverter with highest efficiency but also suitable with the limitation of voltage/current.

This solar PV system has backup from electricity grid to avoid the intermittent energy from solar PV. However, because of TRNSYS limitation, the grid electricity can't be directly model on this simulation. On this report – In the results section – the electricity amount from grid will be shown and it includes the income and expenditure from the selling and buying the electricity, respectively. Furthermore, this PV-RO desalination system is use water tank to become the substitution of battery. This application will minimize the necessity of 24 hours work of reverse osmosis system and limit the hours number of the reverse osmosis system.

3.2 Performance & Economic Indicators

To analysis the performance of reverse osmosis system driven by solar PV system, the indicators of performance have been determined. These variables are each result of reverse osmosis simulation model and solar PV simulation model. Performance indicator for this whole system is shown at Table 2.

Table 2. Performance Indicator

Indicator Name	Symbol	Unit
Total Pump Consumption	$\dot{W}_{pump,total}$	kWh
Specific Energy Consumption of Reverse Osmosis System	SEC	kWh/m^3
Permeate Concentration	C_p	g/l
Permeate Flow Rate/Water Production	$\dot{Q}_p$	l/h
Recovery Ratio	RR	%
Rejection Ratio	Rej	%
Electrical Energy Production from PV	E_{PV}	kWh
Electrical Energy from Grid	E_{grid}	kWh

Solar Fraction	SF	%

Total pumps consumption is obtained from summation of booster pump consumption ($\dot{W}_{feed\ booster\ pump}$), high-pressure pump consumption ($\dot{W}_{feed\ HP\ pump}$), and recirculation pump consumption ($\dot{W}_{recirculation\ pump}$). The correlation for those each pump consumption respectively, as follows [26]:

$$\dot{W}_{feed\ booster\ pump} = \frac{\left(P_{out,booster} - P_{in,booster}\right) \times \dot{Q}_f}{\eta_{booster} \times \eta_{motor}} \tag{3.30}$$

$$\dot{W}_{feed\ HP\ pump} = \frac{\left(P_f - P_{LP}\right) \times (\dot{Q}_f - \dot{Q}_r)}{\eta_{HP} \times \eta_{motor}} \tag{3.31}$$

$$\dot{W}_{feed\ booster\ pump} = \frac{\left(P_f - P_{PX}\right) \times \dot{Q}_r}{\eta_{booster} \times \eta_{motor}} \tag{3.32}$$

where P_{LP} is low-pressure of pumps (1 bar), $\eta_{booster}$ is booster pump efficiency, η_{motor} is electrical motor efficiency, η_{HP} is high pressure pump efficiency, and P_{PX} is pressure recovered by PX energy recovery device (ERD).

Pressure recovered by PX energy recovery device can obtained from PX ERD efficiency (η_{PX}). The equation is expressed as follows [26]:

$$\eta_{PX} = \frac{(P_{PX} - P_{LP}) \times \dot{Q}_r}{(P_r - P_{LP}) \times \dot{Q}_r} \tag{3.33}$$

with knew values of all pump consumptions, the total pump consumption can be calculated with following summation:

$$\dot{W}_{pump\ total} = \dot{W}_{feed\ booster\ pump} + \dot{W}_{feed\ HP\ pump} + \dot{W}_{recirculation\ pump} \tag{3.34}$$

This total pump consumption value is used to calculate specific energy consumption of reverse osmosis system. SEC value is correlated with permeate flow rate/water production and it can be expressed as follows:

$$SEC = \frac{\dot{W}_{pump\ total}}{\dot{Q}_p} \tag{3.35}$$

Rest of performance indicators from RO system simulation (permeate concentration, permeate flow rate/water production, recovery ratio, and rejection ratio) is already explained in above at RO system simulation description. For solar PV system simulation, electrical energy production is obtained from output of inverter (AC Power). Thus, with all this performance indicators, the studies performance of PV-RO system can be concluded. However, as have been stated earlier, there is a backup system from grid electricity on this PV-RO desalination system. Thus, with the results from the calculation and simulation, work of grid electricity can be determined. The equation of grid electricity as following:

$$E_{grid} = \dot{W}_{pump,total} - E_{PV} \tag{3.36}$$

where E_{grid} is consumed grid electricity and E_{PV} is electrical energy produced by solar PV system.

There is also economic indicator that showed in this thesis. Net present value, internal rate of return, payback period, and cost of water become the economic parameters. These values used to describe economically feasible for this desalination project. Furthermore, these values also used to present cash flow analysis for this desalination case.

First parameter is net present value (NPV). This value is measured the difference between the actualized economic savings through the project life time and the investment done. In this thesis, the annual economic saving is assumed to be constant along the years. This parameter is obtained from correlation of economic saving, interest rate, and investment cost which will obtain present value (PV) of each year. NPV is total summation of present value on each years of plant lifetime. However, since it economic saving assumed constant, the equation to described NPV can be expressed as follows [43]:

$$NPV = \frac{ES(1+i)^n - 1}{(1+i)^n} - I_o \tag{3.37}$$

where i is annual interest rate in Indonesia, n is lifetime year of PV-RO desalination plant, I_o is total capital investment cost, and ES is annual economic saving.

Economic saving is obtained from calculation of water production, revenue cost, and electrical energy purchase from grid. However, in this thesis, revenue cost is used cost of potable water in Madura due to simplified the revenue calculation. With following description, the equation is shown as follows:

$$ES = \dot{Q}_{p,annual} \times C_{water} - E_{grid} \times C_{electricity} \tag{3.38}$$

where $\dot{Q}_{p,annual}$ is annual total water production, C_{water} is cost of potable water in Madura (US$ 21), E_{grid} is annual total electrical energy from grid and $C_{electricity}$ is cost of electricity in Madura (US$ 0.1).

After obtained result of NPV, internal rate of return (IRR) can be calculated. Variable i on eq. (3.35) can become IRR with knowing NPV = 0 or break-event point on the end of plant lifetime [43]. Thus, the calculation can be done in reverse with NPV equation. Present value of each year can be also used to calculate payback period and revenue for this desalination plant. The calculation is started from subtracted investment cost with present value at beginning years and after reach break-even point, it would become revenue cost for this desalination plant by addition present value of each year. The period time from started point to break-even point is called as payback period [43].

Last parameter is cost of water production. The cost that used for this thesis is simplified equation and it calculated from capital cost, operational cost, interest rate, and annual total water production. The equation for simplified cost of water (SCOW) as follows [44]:

$$SCOW = \frac{(I_o \times \alpha) + C_{operation}}{\dot{Q}_{p,annual}} \tag{3.39}$$

where $C_{operation}$ is operational expenditure of this desalination system and α is amortisation factor. The latter variable is expressed as follows [44]:

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.40}$$

All the price that used in this thesis will be in dollar and cost of water from this PV-RO desalination system will compare to the cost of potable water at Madura's Island.

3.3 Model Validation

In the beginning of this chapter, it has been said that there are two subsystems model for RO system and PV system performance simulation of calculation. Before using the input of desired parameters, there are validation processes for both models. The reverse osmosis calculation model validation is used input data of scientific paper from Monnot et al. [26]. In other hand, for the PV solar system simulation model is used input data and result of scientific paper from Jimenez et al. [45]. Both of the validation result shown that the reverse osmosis calculation model and PV solar system simulation model has a little difference from the scientific papers results and it means the models are validated.

- Reverse Osmosis System Simulation

Reverse osmosis calculation model that constructs with Engineering Equation Solver (EES) is used initial data and specification manufacturer at the scientific paper. The initial data and specification manufacturer is shown at Table 3.

Table 3. Input of RO Calculation Model

Initial Conditions	
C_f (Feed Solution Concentration)	32 g/l
P_f (Applied Pressure)	55.21 bar

T (Water Temperature)	25°C
$\dot{Q}_f$ (Feed Solution Flow Rate)	2360 l/h
Manufacturer Specification (CSM RE4040-SHN)	
$C_{f,m}$ (Feed Solution Concentration)	32 g/l
A_m (Membrane Area)	6.9 m^2
P_m (Applied Pressure)	55 bar
T_m (Water Temperature)	25°C
RR_m (Recovery Ratio)	8%
$\dot{Q}_{p,m}$ (Permeate Solution Flow Rate)	4.5 m^3/day

With using those of inputs variable, the reverse osmosis calculation model is created. However, this validation only works for one element and it's different with the design of reverse osmosis in this research. Despite of that, the validation is still corresponding to the system that writer has been made. From the paper, we obtained the values of permeate flow rate (Q_p), permeate concentration (C_p), rejection rate, and recovery rate for the system. The results from the model and results from the paper are shown from Table 4.

Table 4. Comparison Table of RO System Simulation

Variable	Paper	Present Work	Error Percentage (%)
$\dot{Q}_p$ (l/h)	189.5	189.8	0.16%
C_p (g/l)	0.0796	0.0741	6.91%
$\dot{Q}_r$ (l/h)	2170.5	2170	0.023%
C_r (g/l)	34.7869	34.7924	0.021%
Rejection Rate (%)	99.75	99.77	0.02%
Recovery Ratio (%)	8.03	8.04	0.12%

From the table, it can be concluded that the error percentage is very small and it looks the model works properly. The permeate flow rate, rejection rate, and recovery ratio has error percentage below 1% and it's proofed the used equation and flow calculation are suitable with the paper. However, the permeate concentration from reverse osmosis unit is quite high compare to other values but the value still below 10%. It means the value is acceptable for the validation test. Hence, the reverse osmosis calculation model can be stated works as properly and can be used for the research.

- Solar PV System Simulation

Solar PV simulation model was constructed with TRNSYS software. As like the validation in the reverse osmosis calculation model, the input data was used from the scientific paper. However, the components are different because the intention of paper and this research also different. The data for validation is shown at Table 5.

Table 5. Input of Solar PV Simulation Model

Manufacturer Specification (DualSun PV Module)	
Photovoltaic Cell Type	Monocrystalline
Cells Number	60
Nominal Power	280 W
Module Efficiency	16.87%
MPP Voltage	31.64 V
MPP Current	8.87 A
Open Circuit Voltage	39.16 V
Short Circuit Current	9.46 A
NOCT (Nominal Operating Cell Temperature)	45°C
V_{OC} Thermal Coefficient	-0.31%/K
I_{SC} Thermal Coefficient	0.045%/K
Efficiency Loss by Temperature	-0.41%/K

From those input variables, the validation simulation can be done. The simulation is used three different weather data which are Fresno (USA), Madison (USA), and Soria (Spain). Fresno and Madison weather data are obtained from weather data on TRNSYS folder and Soria weather data is obtained from Photovoltaic Geographical Information System (PVGIS) website by European Commission [42]. The results validation are hourly and monthly data. However, since the model on this scientific paper is intended to construct the PV/T system, the data that shows only two variables (annual radiation and annual electrical energy production). The comparison table is shown at Table 6.

Table 6. Comparison Table of Solar PV System Simulation

Comparison Table of Annual Radiation (MWh/m^2)			
Location	**Paper**	**Present Work**	**Error Percentage (%)**
Fresno, USA	1.88	1.899	0.99%
Madison, USA	1.42	1.428	0.53%
Soria, Spain	1.62	1.596	1.46%
Comparison Table of Electrical Energy Production (kWh)			
Location	**Paper**	**Present Work**	**Error Percentage (%)**
Fresno, USA	2139.5	2049.2	4.22%

Madison, USA	1758.3	1615.1	8.14%
Soria, Spain	1982.9	1809.9	8.72%

From the Table 6, it can be concluded that the solar PV simulation model has lower values of error percentage. The error percentage of annual radiation values are quite small but for electrical energy production is little bit higher. However, the error percentage still below 10% and it shows that simulation can achieve similarity with scientific paper result. Hence, the solar PV system simulation model is working properly and can be used for this research.

3.4 Input Data of Operational and Design Parameters

The input data of solar PV-RO system for this research is from the weather data of Madura, water condition on Madura, and the assumption condition of the research itself. The table of input data of operational and design parameters are shown at Table 7.

Table 7. Input on Each Components

Component	Input	Value
Solar PV	Ambient Temperature (T_c)	300.23 K
	Total Incident Radiation (G_T)	78400 kWh
	Diffuse Radiation ($G_{T,diff}$)	33435.56 kWh
	Beam Radiation ($G_{T,beam}$)	44964.53 kWh
	Array Slope (β)	-7.03^o
	Module Specification	Table 9
Inverter	Inverter Efficiency ($\eta_{inverter}$)	96.6%
Reverse Osmosis	Permeate Flow/Capacity for First Module ($\dot{Q}_{p,1}$)	95.833 L/h
	Feed Pressure for First Module ($P_{f,1}$)	50.5 bar
	Feed Water Salinity (C_f)	31 g/L
	Feed Water Temperature (T)	29.1^{o}C
	Recovery Ratio for First Module (RR_1)	8%
	Membrane Area ($A_{membrane}$)	3 m^2
	Thickness of the Spacer (h_b)	0.71×10^{-3} m
	Space Between Strands (sbf)	2.79×10^{-3} m
	Length of the Active Membrane Surface (L)	0.96 m
	Module Limitation	Table 12
High Pressure Pump	Pump Efficiency (η_{HP})	75%
Booster Pump	Pump Efficiency ($\eta_{Booster}$)	70%

Energy Recovery Device	ERD Efficiency (η_{PX})	90%
Electrical Motor Efficiency	Motor Efficiency (η_{motor})	98%

The solar PV weather data is obtained from the PVGIS website by European Commission [42]. The weather data is from Bangkalan, Madura and the type are TMY data. From the weather data, it can obtain ambient temperature, total incident radiation, and diffuse radiation. For the array slope data, this simulation is used the longitude value of Bangkalan, Madura. The last input variable is module specification which can obtained from the manufacturer's catalogue. In this research, the module of solar PV is Solar Module SM55 from Siemens company. The specification data of this module is shown at Table 8 [46].

Table 8. Solar Module SM55 Specification [46]

Manufacturer Specification (SM 55 Module)	
Photovoltaic Cell Type	Monocrystalline
Cells Number	36
Nominal Power	55 W
Module Efficiency	12.37%
MPP Voltage	17.4 V
MPP Current	3.15 A
Open Circuit Voltage	21.7 V
Short Circuit Current	3.45 A
NOCT (Nominal Operating Cell Temperature)	45±2^{o}C
V_{OC} Thermal Coefficient	-0.077 V/^{o}C
I_{SC} Thermal Coefficient	1.2 mA/^{o}C

The input data for inverter/regulator is obtained from manufacturer specification. In this research, the inverter/regulator is use UNO-2.0-I from Power-One company [47]. For the TRNSYS program, the data that become the input is only efficiency of inverter. This component has maximum efficiency 96.6%. The hysteresis losses and any losses are neglected in this case and doesn't counted on the simulation.

For the reverse osmosis unit, the inputs data are obtained from laboratory result of seawater concentration on Madura, desired permeate flow rate/water production from the calculation, monthly data of seawater temperature and manufacturer specification of reverse osmosis element. The laboratory testing is done at Indonesia and the data is shown at Table 9. The data contained three locations of measurement, which are west sea, east sea, and middle sea. In this research, the location selected is at east sea due to the closeness with Bangkalan, Madura (location of this research). The salinity in this location is about 31 ppt.

Table 9. Measurement of Seawater Concentration on Madura, Indonesia

Location	Salinity (ppt)	pH
East Sea	31	7.74
Middle Sea	22	7.85
West Sea	32	7.8

For seawater temperature data, it was obtained from *seatemperature.org* website [48]. The location for seawater temperature data is at Tenggun Dajah which are the part of Bangkalan city. The data used is monthly data and it is shown in Table 10. The average seawater is around 29.1ºC with the maximum and minimum values is 30.2ºC and 27.9ºC, respectively. From the website, the measurements of water temperature are provided by the daily satellite reading provided by the NOAA [48].

Table 10. Monthly Seawater Temperature of Tenggun Dajah (Indonesia) [48]

January	**February**	**March**	**April**	**May**	**June**
29.2ºC	28.85ºC	29.3ºC	29.6ºC	29.65ºC	29.1ºC
July	**August**	**September**	**October**	**November**	**December**
28.3ºC	27.9ºC	28.3ºC	29.2ºC	30.1ºC	30.2ºC

The manufacturer for reverse osmosis element in this research is used CSM product with type RE 2540-SHF [40]. In the catalogue for this RO element/module has the operational limitation and the outputs and performance at design conditions of element specification [40]. Those input data from the manufacturer is shown at Table 11. In addition, the characteristics of this RO element is also had the minimum salt rejection about 99.6% and the limitation of permeate recovery rate will no more than 20%. The membrane type is thin-film composite and the RO element configuration is spiral-wound.

Table 11. Technical Specification of CSM RO Element (RE 2540-SHF) [40]

Outputs and Performance at Design Condition	
Seawater Concentration	32000 mg/L (NaCl Solution)
Recovery Rate	8%
Water Temperature	25ºC
Applied Pressure	5.5 MPa
Manufacturer Specification (RE 2540-SHF)	

Maximum Pressure Drop/Element	0.1 MPa
Maximum Operating Pressure	8.27 MPa
Maximum Feed Flow Rate	1.36 m^3/hr
Minimum Concentrate Flow Rate	0.23 m^3/hr
Maximum Operating Temperature	45ºC
Operating pH Range	2.0 – 11.0

Another input variable for the RO unit performance simulation is desired freshwater demand (drinking water in this thesis). The freshwater demand is calculated according to the standard of the World Health Organization (WHO) for human consumption; thereby, 20 liters per day per person is considered [49]. Then the total number people on Bangkalan were searched and the data is obtained from the Regional Body for Planning and Development of Bangkalan. However, since this research is intended to develop a small-scale desalination plant, the target of the consumer is also minimized. For this research, the specific location is Ujung Piring Village and it's located on the coast of east sea at Madura. The total population in this village is 1682 people and from this value the following equation is used:

$$\dot{Q}_p = Total\ Population\ \times WHO\ Standard \tag{3.41}$$

Using the Eq. 3.30, the total freshwater water demand necessary for people in Ujung Piring Village is about 33.64 m^3/day. Because of this research want to explore about small-scale plant, thus from that value, writer took 30% to become target production of desalination plant due to minimize area required for the PV plant. Hence, the desired permeate flow rate or water production from this system has to be equal or more than 10 m^3/day.

For the high-pressure pump, booster pump, and PX energy recovery device, the input data is from manufacturer specification on Monnot et al paper [26] and the values already shown at Table 8. All the variables and values have been shown at following passage. However, the calculation and simulation also consider the following assumptions that have been stated in the chapter 3.1. This following input will use to calculate and simulate for obtain the performance indicator.

3.5 Reference Cost

Type of cost in this research is divided by two categories. There are capital expenditures and operating expenditures. Capital expenditures refers to the funds used by a business to acquire, maintain, and upgrade fix assets [50]. This category also named as investment cost. Operating expenditures refers to the activities costs that associated with the production of goods or services. These costs are correlated into the administrative expenses and operating expenses. List of capital expenditures and operating expenditures are shown at Table 12 and Table 13, respectively.

Table 12. Capital Expenditures Reference Costs

	Direct Capital Cost	
Components	**Sub-Components**	**Specific Cost (Ref)/Percentage**
Solar PV System	PV Modules	US$ 127/Panel [51]
	PV Inverters	US$ 1440/Unit [52]
	PV Land Area	US$ 8.5/m^2
RO System	RO Module	US$ 250/unit [26]
	Pressure Vessel	US$ 1000/unit [26]
	HP Pump	US$ 1300/m^3 [26]
	Electrical Motor for HP Pump	US$ 2500/unit [26]
	Feed Booster Pump + Motor	US$ 1800/unit [26]
	PX Recirculation Pump + Motor	US$ 3000/unit [26]
	PX Cost	US$ 3135/m^3 [26]
	Solar Pond	US$ 9632/acre
	Water Tank	US$ 76/m^3 [53]
	Auxiliary Component and Utilities (e.g., piping)	1.5% from Total RO System Capital Cost [54]
	Building for RO Unit	3.5% from Total RO System Capital Cost [54]
	Site Preparation	1.5% from Total RO System Capital Cost [54]
	Pre-treatment	10% from Total RO System Capital Cost [54]
	Post-treatment	2% from Total RO System Capital Cost [54]
	Indirect Capital Cost	
	Developer Costs	9% from Total Direct Capital Cost [54]
	Engineering Costs	15% from Total Direct Capital Cost [54]
	Financing Cost	10% from Total Direct Capital Cost [54]
	Contingencies	15% from Total Direct Capital Cost [54]
	Working Capital Cost	
	Working Capital	10% from Fixed Capital Cost [55]

In the capital cost, there are three different group which effect the calculation. Direct capital cost is the price for all components or technologies of the system. In other hand, indirect capital cost is the other expenditures that not related to the system components. Summation between direct capital cost and indirect capital cost will give fixed capital cost. In the end, working capital can be obtained and will be added to fixed capital cost for obtained total capital expenditures/CAPEX.

Table 13. Operating Expenditures Reference Costs

Reference Parameters	Specific Cost (Ref)
Plant Operation Labour	US$ 1701/year [56]
Plant Maintenance Labour	US$ 1701/year [56]
Solar Field Maintenance Labour	US$ 1701/year [56]
PV Maintenance Services	0.5% from Total PV System Capital Cost [26]
RO System Maintenance Services	15% from Total RO System Capital Cost [54]
Chemical for Pre-Treatment	US$ 0.65/m^3 [57]
Electricity Tariff Rate	US$ 0.1/kW [58]
RO Membrane Exchange	US$ 1250/10 year [26]
Evaporative Pond	5% from Evaporative Pond Capital Cost [54]
Environmental and Performance Monitoring	5% from Total Operational Expenditure Cost [54]
Indirect O&M Cost	12% from Total Operational Expenditure Cost [54]

Besides reference cost of capital and operational expenditure, there are also economic parameters to be use for calculate economic indicators that have been explained before. These parameters are related to variables cost that don’t include to operational expenditures or capital expenditures. All the economic parameters are shown at Table 14. The values are obtained from actual data at Indonesia or from scientific paper except plant lifetime and salvage value which obtained by assumption

Table 14. Economic Parameters

Economic Parameters	Value
Plant Lifetime	25 years
Annual Plant Overheads	15% from Fixed Capital Cost [54]
Interest Rate	11.79% [59]
Annual Insurances	2% from Fixed Capital Cost [54]
Water Tariff Rate	US$ 21/m^3 [60]
Salvage Value	US$ 0

To finished explanation for this sub-chapter, the calculation to obtained evaporative pond is given and explained. Inside of capital expenditure reference cost, there is a solar pond area calculation based on this following equation [26]:

$$A_{solar\ Pond} = \frac{Q_r}{evaporation\, rate \times pancoeff \times salinity\ ratio} \quad (3.42)$$

where evaporation rate for Class-A pan in Madura is 0.004 m/day [61]. Class A-pan coefficient and salinity ratio is assumed as 70% for each variable.

With known solar pond area, the cost of this component can be expressed as following [26]:

$$Solar\ Pond\ Price\ (\$) = -1276.6 \times A_{solar\ Pond} + 9310 \quad (3.43)$$

where area of solar pond has to be converted into acre.

The price that writer obtained from calculation is US$ 8201 for 0.88 acre. Hence, the price of solar pond component for 1 acre is about US$ 9632.

4. Results and discussion

In this chapter, the results and discussion are divided into three sub-chapter which are simulation and calculation result, PV-RO system on different water temperature in each month, and techno-economic analysis of the PV-RO system design. The analysis of each result is discussed and also the consideration and assumption are provided.

4.1 Simulation Results

The reverse osmosis system performance calculation using EES software and solar PV simulation using TRNSYS software are shown and discussed as follows. By using the input variables provided in chapter 3, both of models (RO system and PV system) have been solved and obtained the outputs. Performance indicator for each component that have been explained previously became the desired output for both models.

4.1.1 RO Desalination System

Reverse osmosis desalination system mathematical model based on Madura seawater data (salinity and temperature) have been evaluated. Using the model input parameter data from chapter 3, the results for the system simulation is shown at Table 15. The following figure is present the values of pressure, concentration of seawater, and volumetric flow rate at each stream (state point). This simulation result also includes energy consumption and pressure exchange on high-pressure pump, booster pump, recirculation pump, and energy recovery device. As have been explained before, target for this desalination system is achieve more than 10 m^3/day for water production and in this case, water production rate is 11.59 m^3/day

Table 15. Reverse Osmosis Desalination System with Value of Stream Variables

States	Volumetric Flow Rate (m^3/day)	Pressure (bar)	Concentration (g/L)
1	28.75	1	31
2	11.59	1	31
3	11.59	51	31
4	17.16	1	31
5	17.16	44.88	31
6	17.16	51	31
7	28.75	51	31
8	11.59	1	0.1275
9	17.16	49.75	46.96
10	17.16	1	46.96

From the figure, it also shows the flow direction of feed solution, permeate solution, and rejected solution. From the results, it can be seen that the permeate concentration of this reverse osmosis desalination system is very small and it indicated the reverse osmosis works properly.

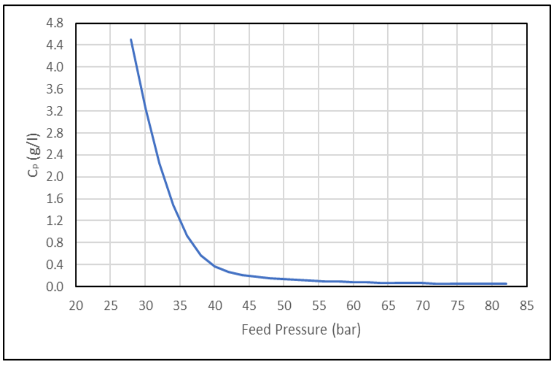
The performance indicators/parameters from this simulation are shown in Table 16. It includes recovery rate of the RO system, rejection rate of the system, total power consummation of the pumps, and RO system's specific energy consumption. All those results shown this system present good performance of desalination system and this RO desalination system also corresponding to the standard limitation of reverse osmosis element specification (Table 11).

Table 16. Performance Parameters of RO Desalination System

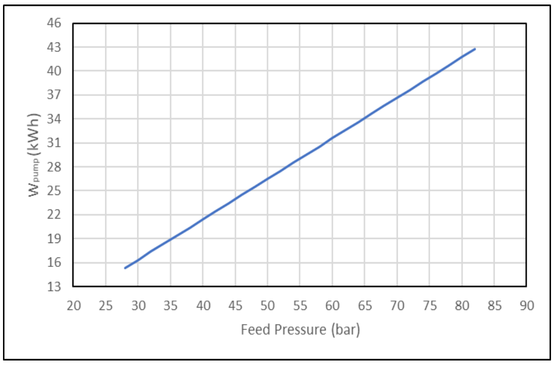
Performance Indicators	**Results**
Recovery Rate	40.32%
Rejection Rate	99.6%
Work Pumps Consumption	26.77 kWh
Specific Energy Consumption	2.3 kWh/m^3

In Fig. 13 also shows the influence of applied high pressure on key performance parameters: permeate concentration (Fig. 13a), pump power consumption (Fig. 13b), and specific energy consumption (Fig. 13c). From these figures, it can be seen that rise in feed pressure make the permeate concentration reduced. On the other hand, increasing applied feed pressure will make the pumps power consumption and specific energy consumption higher. Thus, the value of applied feed pressure has to be optimized to obtained lower pump power consumption and specific energy consumption to the desired value of permeate concentration.

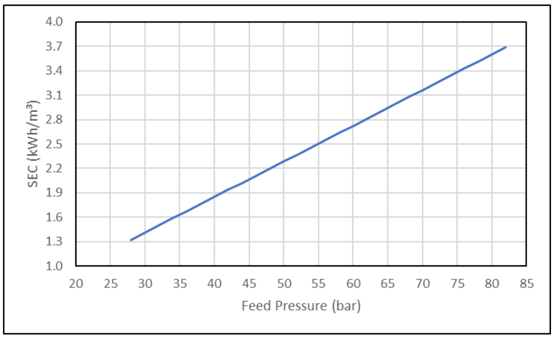
The range for the variation of feed pressure is from 28 bar as the osmotic pressure of the feed solution to 82 bar as the maximum limit of the applied pressure for the selected RO module in this study. Based on Fig. 13 (a-c), it can be seen that the lowest pressure has corresponding results with the best ideal performance which has acceptable permeate concentration and lowest values of pump consumption and specific energy consumption. However, the applied feed pressure has to be higher than 50 bar to achieve the minimum salt rejection rate value of RO system due to limitation specification of RO membrane used. Thus, in this case, applied feed pressure for the RO system is as around 50.5 bar as the minimum value of suitable pressure and can achieve the lowest value of permeate concentration, total power consumption of pumps, and specific energy consumption.



(a)



(b)



(c)

Figures 13. Correlation Pressure between Performance Parameters, (a) Permeate Concentration, (b) Power Pump Consumption, (c) Specific Energy Consumption

All the results for this RO calculation will shown at appendix A. The results shows the performance parameters of each RO element and also other parameters (e.g., mass transfer coefficient, rejection rate). As can be seenfrom these results, the flow of reverse osmosis works are properly calculated and it also describes the process of mass transfer in this component.

4.1.2 Solar PV Simulation

Solar PV simulation results that were done by TRNSYS software with used Madura weather data has been obtained. With the inputs variables and operating parameters from chapter 3 (Table 7, Table 8, Table 9, Table 10, and Table 11), the simulation can result hourly and monthly data of solar PV performance. As have been shown in the performance indicators, this simulation output is electrical energy production from solar PV system. However, in this sub-chapter, the irradiation data with diffuse radiation and beam radiation also shown. The results are from 50 PV modules with array configuration as 10 modules in series and 5 rows in parallel. The monthly results from solar PV simulation are shown at Table 17.

Table 17. Monthly Result of Solar PV Performance Simulation

Months	Solar Irradiation (kWh)	Electricity Energy Production (kWh)

January	3028.63	322.89
February	3538.56	369.80
March	3098.40	326.88
April	3299.83	349.33
May	3920.58	409.27
June	2681.96	287.84
July	3364.11	358.50
August	4294.55	444.17
September	3334.21	352.62
October	3900.22	400.42
November	3646.28	378.93
December	3155.86	333.68

From the table, it can show that the results are very small but it's only for one module. Thus, it shows the potential of solar PV application on Madura's Island. In June, solar irradiation is smallest and would make the electrical energy production also the lowest. On other hand, in August, solar irradiation is highest and would make the electrical energy production also the highest. Total annual solar irradiation in this simulation is 41263.31 kWh and annual electrical energy production is 4334.33 kWh

We can also see the potential months for application of solar PV system in this specific location. The most interesting results from both charts are the different value of DC power and AC power on this system. It shows that from this configuration of solar PV system, the DC and AC power can achieve more than 280 kW per months. It indicates that the solar PV can works maximum as the characteristic of specification. Furthermore, in some months the solar PV module can achieve power more than 400 kW and it indicates on those months the solar PV module can work on highest performance. This condition should be noted and will be use on future calculation.

4.2 PV-RO Desalination System Performance

In this sub-section, the results of PV-RO desalination system performance simulation are provided as follows. These annual performance results were obtained by using seawater temperature and weather data of Madura's Island. The required energy for operating RO system and electrical energy production from PV array system is obtained using the models developed in Chapter 3.

4.2.1 Annual Energy Consumption and Water Production of RO System

With used the calculation model that have been conduct before, energy consumption and water production for along the year can be calculated. The calculation is used parametric table on EES software. Variation of seawater temperature data on each month at one year become the independent variable. Both of these results of RO system are shown at Table 18. Based on the table, it shows the highest consumption of RO system at August and lowest consumption of RO. In other hand, the water production doesn't show much variation data and it makes highest and lowest data are located at several months.

Table 18. Energy Consumption and Water Production Monthly Results

Months	**Q_p (m^3)**	**W_{total} (kWh)**
January	359.29	829.241
February	324.52	749.025
March	359.29	829.205
April	347.7	802.422
May	359.29	829.169
June	347.7	802.492
July	359.29	829.385
August	359.29	829.457
September	347.7	802.631
October	359.29	829.241
November	347.7	802.353
December	359.29	829.098

The highest water production is at the months which have 31 days and lowest production is at February due to has lowest number of days. From this total water production per month, volume of water tank can be determined which will explained in below. Annual water production from this PV-RO system is 4230.35 m^3 and annual energy consumption is 9764 kWh.

From the table, it also shows energy consumption of PV-RO system is varying at each month. However, the different value isn't too significant and it's indicated that the seawater temperature doesn't affect specific energy consumption calculation. Those values also become consideration to determine area of PV array. Furthermore, from the chart we can conclude that the energy necessity of RO is intermittent and can't be stable along the year. We can also see that the water production on each month is quite same. These results are coming from the multiply calculation between permeate flow rate and number of days in each month. Thus, independent variable for these results only number of days and will not make significant differential of water production monthly results.

4.2.2. PV System Configuration

The configuration of the PV system is based on the maximum electrical energy demand of the RO system. It means the selection of PV array area (number of PV panels) are determined by considerate the highest amount of energy that required to operate RO system. From the previous sub-chapter, it can be seen that the highest pump power consumption is in August which is about 829.457 kWh. Besides, we also know from previous results the highest electrical energy production in August. Hence, August was considered for choosing the PV system configuration. The objective is to find the PV array area and number of modules that can generate electrical energy required to cover the demand of the power consumption of the pumps. From several runs of PV system simulation on TRNSYS, suitable range of area are obtained which is 38 m^2 to 43 m^2. Using this total area and a single panel/module area, number of modules can be determined. The best possible configuration is to have 95 modules of PV with configuration of 19 panels in series and 5 rows panels in parallel. The output of electrical energy with this configuration is shown in Table 19. In this table, the required monthly amount of electricity from the utility grid to cover the demand of the RO system is also depicted.

Table 19. Monthly PV Electrical Energy Production, RO Energy Consumption, and Consumed Grid Electricity

Months	**RO Energy Consumption (kWh)**	**Electrical Energy Production (kWh)**	**Consumed Grid Electricity (kW)**
January	829.24	613.49	215.75
February	749.02	702.63	46.40
March	829.21	621.07	208.13
April	802.42	663.72	138.70
May	829.17	777.62	51.55
June	802.49	546.90	255.59
July	829.39	681.15	148.23
August	829.46	843.92	0
September	802.63	669.97	132.66
October	829.24	760.80	68.44
November	802.35	719.96	82.39
December	829.10	633.99	195.11

From the table, we can see the gap value between electricity energy from PV system and pump consumption from RO system. That gap is electricity that will deliver by the grid. we also can see that on August, electricity from PV system can surpass pump consumption and it means the excess electricity can be sold to the grid however because it’s too small, the selling calculation is ignored. Furthermore, there are several months that PV system can delivered the high amount of electricity to RO system. However, on those months there will be also electricity support from grid to operate the RO system since there is a gap that have been explained before. Even though, the amount electricity from the grid is very small and it is indicated that the electricity for RO system is more delivered by PV array. The annual electrical energy production from the PV system is about 8235.23 kW and annual supply electrical energy from utility grid is about 1528.48 kWh.

For instance, in February and May, the electricity from the utility grid is very small and it indicates PV-RO system also works on its best performance. However, several months need more electricity from the grid such as January, March, and June. In these three months, it is required more than 200 kW of electrical energy from the grid to operate the RO desalination system. Hence, in these months the desalination plant will have higher operational costs since electricity has to be purchased from the utility grid.

4.3 Solar Contribution

Solar contribution is the performance parameter that shows the contribution of solar energy to available energy demand on whole system. This value is showing the electricity that can fulfilled by solar energy system. Since PV system is become the selection for this research, the electricity energy that produced will compared to energy demand or RO pump consumption. Solar fraction results are shown at Table 20.

Table 20. Solar Contribution

Months	**RO Energy Consumption (kW)**	**Electrical Energy Production (kW)**	**Solar Contribution (%)**
January	829.24	613.49	74%
February	749.02	702.63	94%
March	829.21	621.07	75%
April	802.42	663.72	83%
May	829.17	777.62	94%
June	802.49	546.90	68%
July	829.39	681.15	82%
August	829.46	843.92	100%
September	802.63	669.97	83%
October	829.24	760.80	92%
November	802.35	719.96	90%
December	829.10	633.99	76%

As have been cleared before, solar Fraction on August will be more than 100% because the electricity energy from PV system can overcome the necessity energy of RO pumps. However, on other months the solar fraction value will be variate and there will be not any value that achieve 100%. It means the

PV system hasn't fully deliver the electricity to the RO pumps. From the table, it can see that the lowest solar fraction is on June which about 68%. This value is small because the produced electricity energy on this month is smallest compare to other months likes that have been written before. In conclusion, it has been seen that all the values of solar fraction are more than 50% and it means the PV system can handle the intensive-energy from RO pump. In addition, annual solar contribution of PV system in this specific desalination system is 84%. This value is indicated that PV system supply more electrical energy and can be stated as main energy source of this desalination system.

4.4 Economic Analysis

In this sub-chapter, results of technical analysis and economic analysis are shown. Solar fraction is the technical analysis that will be discuss. In other hand, calculation of production cost based on capital expenditure (CAPEX) and operational expenditure (OPEX) is the economic analysis for this research.

4.4.1 CAPEX Calculation

Using the reference cost from Chapter 3 (Table 12), capital cost calculation can be established. The CAPEX table is show at Table 21 and cost proportional is shown at Fig.14. All coefficient/parameters for each component that shown in the table and figure is based on the PV-RO design system which have been explained in Chapter 2.

Table 21. Estimated CAPEX of PV-RO Desalination System and Its Components

Direct Capital Cost		
Components	**Coeff/Parameters**	**Cost**
PV Modules	95	US$ 12065
PV Inverters	2	US$ 2880
Land Area	80	US$ 680
RO Module	5	US$ 1250
Pressure Vessel	1	US$ 1000
HP Pump	0.49	US$ 637
Electrical Motor for HP Pump	1	US$ 2500
Feed Booster Pump + Motor	1	US$ 1800
PX Recirculation Pump + Motor	1	US$ 3000
PX Cost	0.72	US$ 2580
Solar Pond	8755	US$ 8433
Water Tank	180	US$ 13676
Auxiliary Components and Utilities (e.g., piping)	1.5%	US$ 533
Building for RO Unit	3.5%	US$ 1786

Site Preparation	1.5%	US$ 792
Pre-treatment	10%	US$ 3788
Post-treatment	2%	US$ 733
Indirect Capital Cost		
Financing Cost	10%	US$ 5740
Contingencies	15%	US$ 8610
Developer Cost	9%	US$ 5166
Engineering Cost	15%	US$ 8610
FIXED CAPITAL EXPENDITURE		US$ 85527
Working Capital		
Working Capital Cost	10%	US$ 8553
TOTAL CAPITAL EXPENDITURE		US$ 94079

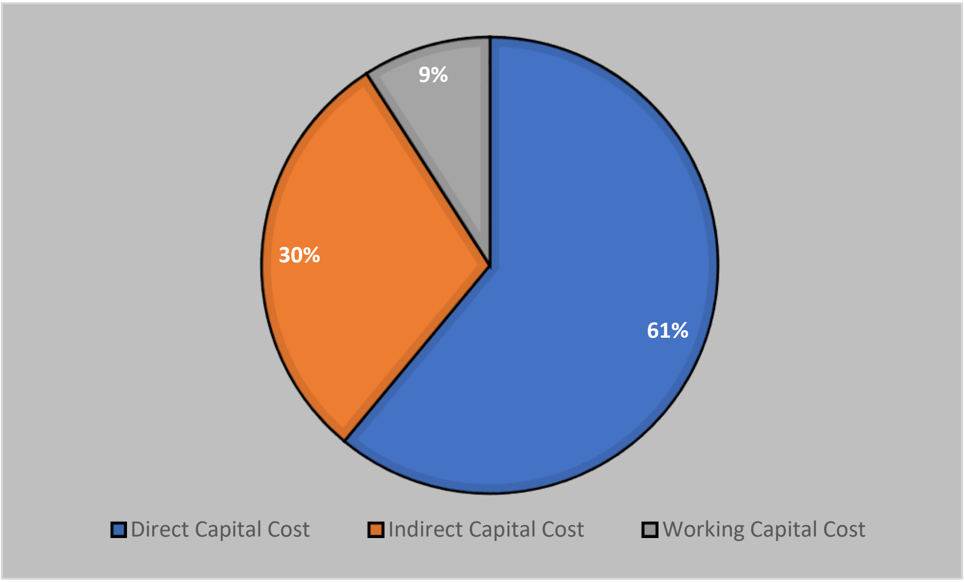


Figure 14. CAPEX Cost Breakdown Percentage

From the table and figure, it can be concluded that direct capital cost or components cost are the most expensive for capital cost. More than half of the total capital cost is from direct capital cost. If we see on the most expensive in direct capital cost is price of RO desalination system components. Since total component of RO desalination system is more than solar PV system, the price would be higher. All the prices are estimation price but corresponding to the reference cost that show on Table 12.

4.4.2 OPEX Calculation

Using the reference cost from Chapter 3 (Table 13), operational cost calculation can be established. The OPEX table is show at Table 22 and cost proportional is shown at Fig.15. All coefficient or parameters for each component that shown in the table and figure is based on the assumption of this PV-RO desalination system.

Table 22. OPEX Calculation

Categories	Components	Coeff/Parameters	Cost
PV Operational & Maintenance Cost	PV Plant Operation Labour	1	US$ 425
	PV Plant Maintenance Labour	1	US$ 425
	PV Solar Field Maintenance Labour	1	US$ 425
	PV Maintenance Services	1	US$ 490
RO Operational & Maintenance Cost	RO Operation Labour	1	US$ 425
	RO Maintenance Labour	1	US$ 425
	RO Maintenance Services	1	US$ 275
	RO Chemical Pre-treatment	10494	US$ 6821
	RO Membrane Exchange	1	US$ 100
	Evaporative Pond	5%	422
Indirect Operational & Maintenance Cost	Environmental and Performance Monitoring	5%	1120
	Others Indirect O&M Cost	12%	2689
TOTAL OPERATIONAL EXPENDITURE			US$ 26219

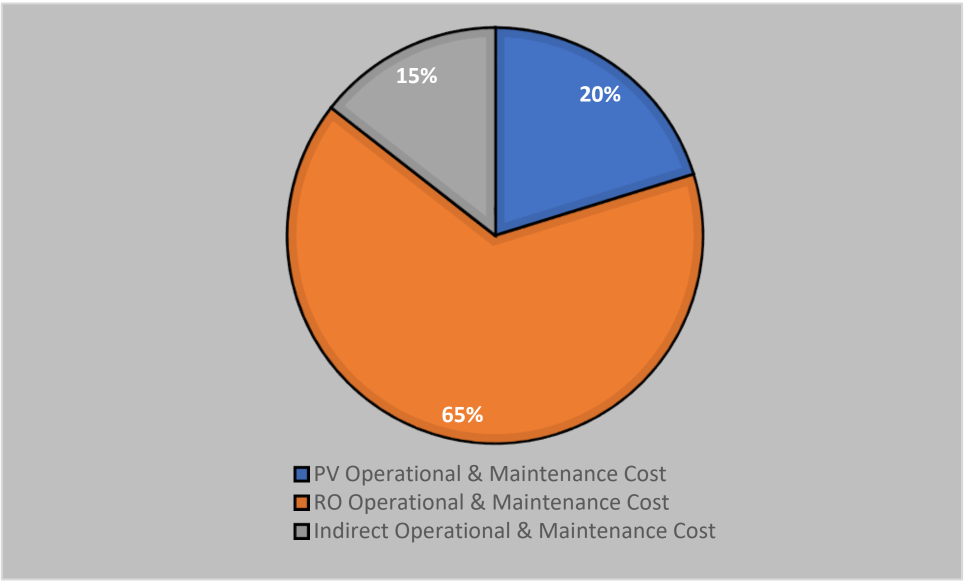


Figure 15. OPEX Cost Breakdown Percentage

From the table and figure, it can be concluded that RO operational and maintenance cost is most expensive for operation and maintenance cost. These results indicate that energy source fuel isn't become the most expensive price for desalination operation which in this thesis is from solar PV system. It shows that application of PV-RO desalination system can decrease utility of fossil fuel and decrease the operation cost.

4.4.3 Net Present Value and Payback Period

With used total capital expenditure (CAPEX) and total operational expenditure (OPEX), net present value for this desalination plant with 25 years lifetime can be calculated. Inside NPV calculation, there will be also net cash inflow every year (assumed to be constant) and present value for this desalination plant every year. The calculation is started from find NPV parameters by used economic parameters that have been shown at Table 14. NPV parameters consist of total capital cost, annual overhead, annual insurances, annual depreciation cost, annual operation cost, and economic saving. From these parameters, almost variable already had on previous calculation. To calculate annual depreciation cost can used equation as follows:

$$Annual\ Depreciation\ Cost = \frac{Total\ Capital\ Cost - Salvage\ Value}{Plant\ Lifetime} \tag{4.1}$$

where salvage value and plant lifetime are already shown at Table 16. All the NPV parameters values are shown at Table 23.

Table 23. NPV Parameters

Cost Variable	Value
Total Capital Cost	US 94709
Annual Overhead	US$ 12829
Annual Insurances	US$ 1711
Annual Depreciation Cost	US$ 3763
Annual Operation Cost	US$ 26219
Economic Saving	US$ 90081

With following values, net cash inflow can be directly calculated by subtracting economic saving with annual overhead, annual insurances, annual depreciation cost, and annual operation cost. This value will be constant every year since all NPV parameters also assumed to be constant every. Thus, with known net cash inflow, Results of present value and net present value can be obtained. Value of these three variables (net cash inflow, present value, and net present value) are shown at Table 24. With this table, we can also calculate IRR (Internal rate of return) for this desalination plant. In this thesis, value of IRR is divided into six groups. The IRR values are available on payback time and every 5 years of lifetime. All IRR values are higher than interest rate which make this plant is more desirable to be invested.

Table 24. NPV Results Every Year & IRR Results

Year	Net Cash Inflow	Present Value	Net Present Value	IRR
0	-94079	-94079	-	
1	45559	40754	-53326	
2	45559	36456	-16870	
3	45559	32611	15741	21%
4	45559	29172	44913	
5	45559	26095	71008	39%
6	45559	23343	94351	
7	45559	20881	115232	
8	45559	18679	133910	
9	45559	16709	150619	
10	45559	14947	165566	47%
11	45559	13370	178936	
12	45559	11960	190896	
13	45559	10699	201595	
14	45559	9570	211165	
15	45559	8561	219726	48%
16	45559	7658	227385	
17	45559	6850	234235	
18	45559	6128	240363	
19	45559	5482	245845	
20	45559	4904	250748	48%
21	45559	4386	255135	
22	45559	3924	259058	
23	45559	3510	262568	
24	45559	3140	265708	
25	45559	2809	268517	48%

From the table, it can be seen at year 0, all the results are negative or empty. This year is indicated starting time of plant construction. In this thesis, the plant construction only takes 1 year and you can see on the table, there is net cash flow on year 1. This table also can determine payback period for this desalination plant. The chart of payback period is shown at Fig. 16.

IRR value is calculated at NPV = 0 or at payback time. For this desalination system, IRR is about 21%. This value is higher than interest rate which make this is more desirable to be invested. In other hand, IRR values every 5 years of lifetime also shows higher value than interest rate and it would keep increased until the last year of the design lifetime.

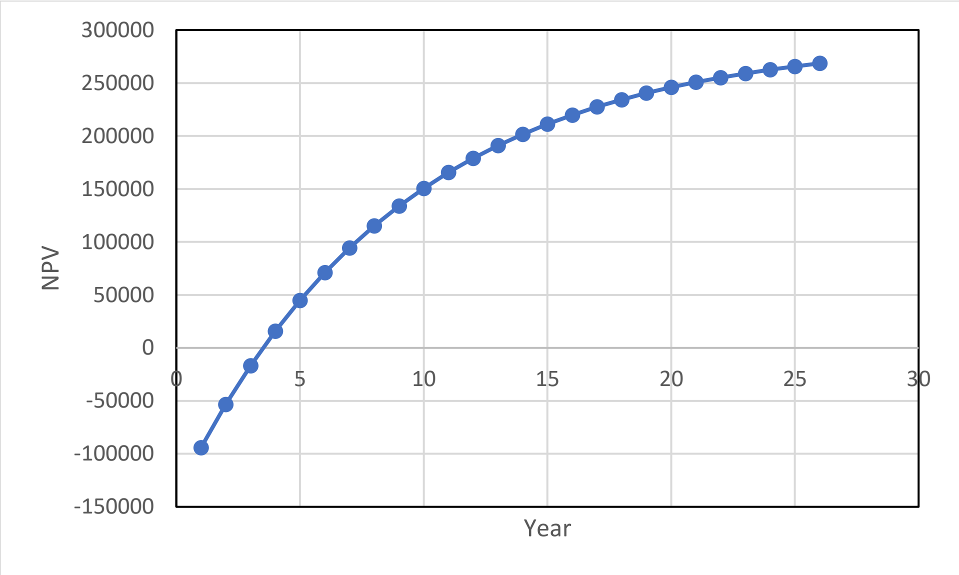


Figure 16. Payback Period

According to the chart, it seen that the desalination plant will have NPV is equal to zero between the second year and third year. This result indicates the potential of PV-RO desalination plant in Madura's Island. Furthermore, it also shows profit for this PV-RO desalination plant along the year.

4.4.4 Specific Water Cost Production Cost

With know all the necessary variables, we can calculate cost of water for this desalination plant. The calculation is starting from amortization factor with Eq. (3.40) and it shows as follows:

$$\alpha = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.1179(1+0.1179)^{25}}{(1+0.1179)^{25}-1} = 0.13 \tag{4.2}$$

With used this value, Eq. (3.41) for calculate cost of water in this desalination plant can be done. Thus, the calculation is shown as follows:

$$SCOW = \frac{(I_o \times \alpha) + C_{operation}}{\dot{Q}_{p,annual}} = \frac{(US\$\,94079 \times 0.13) + US\$\,26372}{4230.35\ m^3} = US\$\ {}^{9.03}/_{m^3} \tag{4.3}$$

This cost production can compete the price of branded water in Indonesia. The branded potable water in Madura has variation of price depends on the package. The common package is gallon of potable water and it contains 19 litres. One gallon of potable water in Madura is about 0.36 USD – 0.50 USD [60]. Thus, the potable water price in Madura is about US$ 21.33/m^3. This price is a quite expensive than the water cost using PV-RO desalination system in Madura's Island. Therefore, application of PV-RO desalination system can profitable and shifting those branded potable water.

5. Conclusion

PV-RO desalination system can become the suitable technology to be install in Madura’s Island. The geographical condition and weather condition showing this location are potential to install this kind of desalination system. Furthermore, this desalination system can overcome water scarcity issue on Madura, especially at drought season. This system can fulfil partly water demand for community in Ujung Piring Village, Madura and it indicates this system could become one of solution to water issue. Application of PV-RO desalination plant on Madura’s Island has big potential to alleviate the water scarcity issue while reducing the adverse impact on the environment. Based on the results obtained in this thesis, the following conclusions on the possible implementation of PV-RO desalination system on Madura Island are made:

- For the production of potable water with a Reverse Osmosis system using Madura seawater and weather data, the specific energy consumption of the system is about 2.3 kWh/m^3.
- Water Production of this PV-RO desalination system is 11.53 m^3/day and annual water production is 4230.5 m^3.
- The solar PV system can produce the highest electricity August and the lowest electricity in June.
- The optimum configuration of the solar PV system in this study is 95 panels with 19 panels in series and 5 rows in parallel.
- Solar contribution of PV system to handle electrical energy demand of RO pumps is more than 60%. On August, all electrical energy demand of RO pumps can fully deliver by solar PV system (100% Solar Contribution).
- Total capital cost of PV-RO desalination system design is US$ 94709 and total operational cost of PV-RO desalination system design is US$ 26219.
- Components cost for RO desalination system is the expensive cost from capital cost of PV-RO desalination system. Operational & maintenance cost for RO desalination system is also the expensive cost from all operational & maintenance cost of PV-RO desalination system
- Payback period of this PV-RO desalination system plant is between second and third year of plant operation.
- Lowest IRR value is at payback time (NPV=0) and highest IRR value is at last year of plant lifespan (Highest NPV). The values are 21% and 48%, respectively.
- The cost of water production using the proposed PV-RO desalination system is about US$ 9.03/m^3. This price is cheaper than actual potable water price in Madura which about US$ 21.33.

References

[1] M. T. Mito, X. Ma, H. Albuflasa, and P. A. Davies, “Reverse osmosis (RO) membrane desalination driven by wind and solar photovoltaic (PV) energy: State of the art and challenges for large-scale implementation,” *Renew. Sustain. Energy Rev.*, vol. 112, pp. 669–685, 2019, doi: 10.1016/j.rser.2019.06.008.

[2] WHO, “Drinking-water,” 2020. https://www.who.int/news-room/fact-sheets/detail/drinking-water.

[3] M. Shatat and S. B. Riffat, “Water desalination technologies utilizing conventional and renewable energy sources,” *Int. J. Low-Carbon Technol.*, vol. 9, no. 1, pp. 1–19, 2014, doi: 10.1093/ijlct/cts025.

[4] C. Murray and A. Lopez, *The World Health Report*. Geneva, Switzerland: WHO, 2002.

[5] S. A. Kalogirou, “Seawater desalination using renewable energy sources,” *Prog. Energy Combust. Sci.*, vol. 31, no. 3, pp. 242–281, 2005, doi: 10.1016/j.pecs.2005.03.001.

[6] P. G. Youssef, R. K. Al-Dadah, and S. M. Mahmoud, “Comparative analysis of desalination technologies,” in *Energy Procedia*, 2014, vol. 61, pp. 2604–2607, doi: 10.1016/j.egypro.2014.12.258.

[7] H. M. El-Dessouky, Hisham T. Ettouny, *Fundamentals of Salt Water Desalination*. Elsevier, 2002.

[8] K. AL-Shaila and O. Javier, “Optimum design of PV-RO system solar powered sea water desalination without storage in Saudi Arabia (Case study),” in *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2019*, 2020, pp. 987–996, doi: 10.18086/swc.2019.19.01.

[9] J. C. Crittenden, R. R. Trussell, D. W. Hand, K. J. Howe, and G. Tchobanoglous, *MWH’s Water Treatment: Principles and Design, Third Edition*. John Wiley and Sons, Inc., 2012.

[10] M. Wilf and C. Bartels, “Optimization of seawater RO systems design,” *Desalination*, vol. 173, no. 1, pp. 1–12, 2005, doi: 10.1016/j.desal.2004.06.206.

[11] D. Herold and A. Neskakis, “A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria,” *Desalination*, vol. 137, no. 1–3, pp. 285–292, 2001, doi: 10.1016/S0011-9164(01)00230-2.

[12] N. Voutchkov, *Pretreatment for Reverse Osmosis Desalination*. Elsevier, 2017.

[13] B. S. Richards and A. I. Schäfer, “Photovoltaic-powered desalination system for remote Australian communities,” *Renew. Energy*, vol. 28, no. 13, pp. 2013–2022, 2003, doi:

10.1016/S0960-1481(03)00081-8.

[14] W. Nookuea, P. E. Campana, and J. Yan, “Evaluation of solar PV and wind alternatives for self renewable energy supply: Case study of shrimp cultivation,” in *Energy Procedia*, 2016, vol. 88, pp. 462–469, doi: 10.1016/j.egypro.2016.06.026.

[15] F. Calise, F. L. Cappiello, R. Vanoli, and M. Vicidomini, “Economic assessment of renewable energy systems integrating photovoltaic panels, seawater desalination and water storage,” *Appl. Energy*, vol. 253, no. May, 2019, doi: 10.1016/j.apenergy.2019.113575.

[16] H. Rezk, M. A. Abdelkareem, and C. Ghenai, “Performance evaluation and optimal design of stand-alone solar PV-battery system for irrigation in isolated regions: A case study in Al Minya (Egypt),” *Sustain. Energy Technol. Assessments*, vol. 36, 2019, doi: 10.1016/j.seta.2019.100556.

[17] A. Al-Zahrani, J. Orfi, Z. Al-Suhaibani, B. Salim, and H. Al-Ansary, “Thermodynamic analysis of a Reverse Osmosis desalination unit with energy recovery system,” in *Procedia Engineering*, 2012, vol. 33, pp. 404–414, doi: 10.1016/j.proeng.2012.01.1220.

[18] H.-J. Oh, T.-M. Hwang, and S. Lee, “A simplified simulation model of RO systems for seawater desalination,” *Desalination*, vol. 238, no. 1–3, pp. 128–139, 2009, doi: 10.1016/j.desal.2008.01.043.

[19] Maps of World, “Indonesia Map,” 2020. https://www.mapsofworld.com/indonesia/.

[20] W. Y. Lam, J. Chatterton, S. Sim, M. Kulak, A. Mendoza Beltran, and M. A. J. Huijbregts, “Estimating greenhouse gas emissions from direct land use change due to crop production in multiple countries,” *Sci. Total Environ.*, vol. 755, 2021, doi: 10.1016/j.scitotenv.2020.143338.

[21] K. P. Aprilianti, N. A. Baghta, D. R. Aryani, F. H. Jufri, and A. R. Utomo, “Potential assessment of solar power plant: A case study of a small island in Eastern Indonesia,” in *IOP Conference Series: Earth and Environmental Science*, 2020, vol. 599, no. 1, doi: 10.1088/1755-1315/599/1/012026.

[22] A. Azahra, K. D. Syahindra, D. R. Aryani, F. H. Jufri, and I. M. Ardita, “Optimized configuration of photovoltaic and battery energy storage system (BESS) in an isolated grid: A case study of Eastern Indonesia,” in *IOP Conference Series: Earth and Environmental Science*, 2020, vol. 599, no. 1, doi: 10.1088/1755-1315/599/1/012017.

[23] M. Eltawil, “Renewable Energy Powered Desalination Systems: Technologies and Economics-State of the Art,” *Recommendations*, vol. 12, no. 1, pp. 1–38, 2008, doi: 10.1007/s12045-015-0272-6.

[24] L. Rizzuti, H. Ettouney, and A. Cipollina, *Solar Desalination for the 21 Century NATO Security through Science Series*. 2006.

[25] S. S. of Demographic, “Indonesia Population Projection,” 2013. doi: 10.1007/BF00830441.

[26] M. Monnot, G. D. M. Carvajal, S. Laborie, C. Cabassud, and R. Lebrun, “Integrated approach in eco-design strategy for small RO desalination plants powered by photovoltaic energy,” *Desalination*, vol. 435, no. February 2017, pp. 246–258, 2018, doi: 10.1016/j.desal.2017.05.015.

[27] K. Bououni, T. Jaber, and S. Elbehissy, “Optimizing the design of PV Solar Reverse Osmosis Unit (RO/PV) by using genetic algorithms for Abu Dhabi climate,” *Fluid Dyn. Mater. Process.*, vol. 13, no. 2, pp. 127–141, 2017, doi: 10.3970/fdmp.2017.013.127.

[28] A. Ghermandi and R. Messalem, “Solar-driven desalination with reverse osmosis: The state of the art,” *Desalin. Water Treat.*, vol. 7, no. 1–3, pp. 285–296, 2009, doi: 10.5004/dwt.2009.723.

[29] D. Manolakos, E. S. Mohamed, I. Karagiannis, and G. Papadakis, “Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia island,” *Desalination*, vol. 221, no. 1–3, pp. 37–46, 2008, doi: 10.1016/j.desal.2007.01.066.

[30] A. Al-Karaghouli, D. Renne, and L. L. Kazmerski, “Technical and economic assessment of photovoltaic-driven desalination systems,” *Renew. Energy*, vol. 35, no. 2, pp. 323–328, 2010, doi: 10.1016/j.renene.2009.05.018.

[31] Malki Ahmed Al, Amri Mohamme Al, and Jabri Hamoud Al, “Experimental study of using renewable energy in the rural areas of Oman,” *Renew. Energy*, vol. 14, no. 1–4, pp. 319–324, 1998, doi: 10.1016/S0960-1481(98)00084-6.

[32] G. Petersen, S. Fries, J. Mohn, and A. Müller, “Wind and solar-powered reverse osmosis desalination units - description of two demonstration projects-,” *Desalination*, vol. 31, no. 1–3, pp. 501–509, 1979, doi: 10.1016/S0011-9164(00)88553-7.

[33] D. G. Harrison, G. E. Ho, and K. Mathew, “Desalination using renewable energy in Australia,” *Renew. Energy*, vol. 8, no. 1–4, pp. 509–513, 1996, doi: 10.1016/0960-1481(96)88909-9.

[34] J. M. Sanchez, N. S. Castillo, and R. S. Castillo, “Mathematical Model for Isobaric Energy Recovery Devices,” *IDA World Congr.*, 2007.

[35] T. M. Mansour, T. M. Ismail, K. Ramzy, and M. Abd El-Salam, “Energy recovery system in small reverse osmosis desalination plant: Experimental and theoretical investigations,” *Alexandria Eng. J.*, vol. 59, no. 5, pp. 3741–3753, 2020, doi: 10.1016/j.aej.2020.06.030.

[36] M. Cheryan, *Ultrafiltration and Microfiltration Handbook, Second Edition*. CRC Press, 1998.

[37] F-Chart Software, “Engineering Equation Solver,” 2021. http://fchartsoftware.com/.

[38] Thermal Energy System Specialists LLC, “Transient System Simulation Tool,” 2021. http://www.trnsys.com/contact/index.html.

[39] J. H. Lienhard IV and J. H. Lienhard V, *A Heat Transfer Textbook Fifth Edition*. Phlogiston Press, 2019.

[40] Lenntech, “CSM-2540-SHF,” 2019.

[41] Lenntech, “RE 4040 -SHN,” 2019.

[42] European Commision, “Photovoltaic Geographical Information System (PVGIS),” 2019. https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY.

[43] M. Papapetrou, A. Cipollina, U. La Commare, G. Micale, G. Zaragoza, and G. Kosmadakis, “Assessment of methodologies and data used to calculate desalination costs,” *Desalination*, vol. 419, no. March, pp. 8–19, 2017, doi: 10.1016/j.desal.2017.05.038.

[44] M. Kettani and P. Bandelier, “Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco,” *Desalination*, vol. 494, no. April, p. 114627, 2020, doi: 10.1016/j.desal.2020.114627.

[45] J. A. Aguilar-Jiménez *et al.*, “Techno-economic analysis of hybrid PV/T systems under different climate scenarios and energy tariffs,” *Sol. Energy*, vol. 212, no. January, pp. 191–202, 2020, doi: 10.1016/j.solener.2020.10.079.

[46] Siemens, “Solar module SM55,” 1997.

[47] Power One, “UNO-2.0-L & UNO-2.5-L General Specifications,” 2013.

[48] National Oceanic and Atmospheric Administration, “Monthly Seawater Temperature on Tenggun Dajah,” 2021. https://www.seatemperature.org/asia/indonesia/tenggun-dajah.htm.

[49] Asian Development Bank, *Indonesia Country Water Assessment*. 2016.

[50] Almar Water Solutions, “Desalination Technologies and Economics: CAPEX, OPEX and Technological Game Changers,” *Cent. Mediterr. Integr. Mediterr. Reg. Tech. Meet.*, 2016, [Online]. Available: http://www.cmimarseille.org/sites/default/files/newsite/library/files/en/1.6. C. Cosin_ Desalination technologies and economics_ capex%2C opex and technological game changers to come -ilovepdf-compressed.pdf.

[51] Tokopedia, “Siemens Solar SM 55 Price,” 2019. https://www.tokopedia.com/rasukastore/ft-18v-55w-flexible-monocrystalline-solar-panel-solar-battery-arge?refined=true&whid=0.

[52] Ebay, “Inverter Power-One Price,” 2021. https://www.ebay.com/itm/UNO-2-5-I-OUTD-US-Power-One-UNO-2-5-I-OUTD-US-2500-Watt-String-Inverter-Aurora-/133104127917.

[53] Bukalapak, “Water Tank Prince,” 2018. https://www.bukalapak.com/p/industrial/industrial-lainnya/xqdt9l-jual-toren-air-tangki-air-penampungan-air-5000-liter-5000l-5000ltr-gratis-ongkir?from=list-product&pos=0.

[54] World Bank, “The Role of Desalination in an Increasingly Water-Scarce World,” *Role Desalin. an Increasingly Water-Scarce World*, no. March, 2019, doi: 10.1596/31416.

[55] N. Ghaffour, T. M. Missimer, and G. L. Amy, “Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability,” *Desalination*, vol. 309, pp. 197–207, 2013, doi: 10.1016/j.desal.2012.10.015.

[56] A. D. Putera, “Standard Salary of Engineer at Indonesia,” *Kompas*, 2018. https://ekonomi.kompas.com/read/2018/05/02/070000826/berapa-gaji-karyawan-di-sektor-konstruksi-manufaktur-dan-energi-di-indonesia?page=all.

[57] G. Azinheira, R. Segurado, and M. Costa, “Is renewable energy-powered desalination a viable solution for water stressed regions? A case study in Algarve, Portugal,” *Energies*, vol. 12, no. 24, 2019, doi: 10.3390/en12244651.

[58] I. N. Widiasa and L. A. Yoshi, “International Journal of Science and Engineering (IJSE) Techno-Economy Analysis A Small Scale Reverse Osmosis System for Brackish Water Desalination,” vol. 10, no. April, pp. 51–57, 2016.

[59] WACC Expert, “Interest Rate at Indonesia,” 2021. http://www.waccexpert.com/.

[60] M. Yusuf *et al.*, “Analisis Faktor-Faktor yang Mempengaruhi Permintaan Air Minum Isi Ulang,” vol. 6, pp. 103–112, 2016.

[61] T. Wati, A. Sopaheluwakan, and Fatkhuroyan, “Comparison pan evaporation data with global land-surface evaporation GLEAM in Java and Bali Island Indonesia,” *Indones. J. Geogr.*, vol. 50, no. 1, pp. 87–96, 2018, doi: 10.22146/ijg.30926.

- **Appendix A – Full results from simulation of RO desalination system**

RESULTS FROM RO CALCULATION BY EES - 1

Unit Settings: SI C kPa kJ mass deg

A_1 = 2,006 [L/(h*bar*m^2)]	A_2 = 1,994 [L/(h*bar*m^2)]	A_3 = 1,98 [L/(h*bar*m^2)]	A_4 = 1,966 [L/(h*bar*m^2)]	A_5 = 1,95 [L/(h*bar*m^2)]	A_m = 1,831 [L/(h*bar*m^2)]
$A_{T,ref}$ = 1,63 [L/(h*bar*m^2)]	B_1 = 0,0001275 [g/L]	B_2 = 0,0001275 [g/L]	B_3 = 0,0001275 [g/L]	B_4 = 0,0001275 [g/L]	B_5 = 0,0001275 [g/L]
B_m = 0,0001008 [g/L]	B_o = 0,2489 [g/L]	B_{ref} = -2290 [1/K]	C_f = 31 [g/L]	$C_{f,1}$ = 31 [g/L]	$C_{f,2}$ = 33,69 [g/L]
$C_{f,3}$ = 36,61 [g/L]	$C_{f,4}$ = 39,78 [g/L]	$C_{f,5}$ = 43,22 [g/L]	$C_{f,m}$ = 32 [g/L]	$C_{m,1}$ = 32,22 [g/L]	$C_{m,2}$ = 34,95 [g/L]
$C_{m,3}$ = 37,86 [g/L]	$C_{m,4}$ = 40,98 [g/L]	$C_{m,5}$ = 44,32 [g/L]	$C_{m,m}$ = 33,33 [g/L]	C_p = 0,1276 [g/L]	$C_{p,1}$ = 0,09377 [g/L]
$C_{p,2}$ = 0,1132 [g/L]	$C_{p,3}$ = 0,1423 [g/L]	$C_{p,4}$ = 0,1848 [g/L]	$C_{p,5}$ = 0,2522 [g/L]	$C_{p,m}$ = 0,07147 [g/L]	C_r = 46,96 [g/L]
$C_{r,1}$ = 33,69 [g/L]	$C_{r,2}$ = 36,61 [g/L]	$C_{r,3}$ = 39,78 [g/L]	$C_{r,4}$ = 43,22 [g/L]	$C_{r,5}$ = 46,96 [g/L]	$C_{r,m}$ = 34,78 [g/L]
$\Delta_{\Phi,1}$ = 27,63 [bar]	$\Delta_{\Phi,2}$ = 29,55 [bar]	$\Delta_{\Phi,3}$ = 32 [bar]	$\Delta_{\Phi,4}$ = 34,61 [bar]	$\Delta_{\Phi,5}$ = 37,39 [bar]	$\Delta_{\Phi,m}$ = 28,22 [bar]
$\Delta_{P,1}$ = 18,75 [kPa]	$\Delta_{P,2}$ = 16,56 [kPa]	$\Delta_{P,3}$ = 14,66 [kPa]	$\Delta_{P,4}$ = 13 [kPa]	$\Delta_{P,5}$ = 11,56 [kPa]	$\Delta_{P,m}$ = 31,59 [kPa]
D_1 = 2,126E-09 [m^2/s]	D_2 = 2,113E-09 [m^2/s]	D_3 = 2,099E-09 [m^2/s]	D_4 = 2,083E-09 [m^2/s]	D_5 = 2,067E-09 [m^2/s]	$d_{h,1}$ = 0,00142 [m]
$d_{h,2}$ = 0,00142 [m]	$d_{h,3}$ = 0,00142 [m]	$d_{h,4}$ = 0,00142 [m]	$d_{h,5}$ = 0,00142 [m]	$d_{h,m}$ = 0,00142 [m]	D_m = 1,667E-09 [m^2/s]
$D_{T,ref}$ = 1,484E-09 [m^2/s]	$\eta_{Booster}$ = 70 [%]	η_{HP} = 75 [%]	η_{Motor} = 98 [%]	η_{PX} = 90 [%]	f_1 = 2,466 [-]
f_2 = 2,573 [-]	f_3 = 2,69 [-]	f_4 = 2,819 [-]	f_5 = 2,961 [-]	f_m = 2,234 [-]	G = 0,2545 [-]
h_b = 0,00071 [m]	i = 2 [-]	J_1 = 43,69 [L/(m^2*h)]	J_2 = 39,23 [L/(m^2*h)]	J_3 = 33,81 [L/(m^2*h)]	J_4 = 28,16 [L/(m^2*h)]
J_5 = 22,28 [L/(m^2*h)]	J_m = 46,91 [L/(m^2*h)]	k_1 = 0,0003143 [m/s]	k_2 = 0,0002956 [m/s]	k_3 = 0,0002778 [m/s]	k_4 = 0,0002609 [m/s]
k_5 = 0,0002449 [m/s]	k_m = 0,0003191 [m/s]	L = 0,96 [m]	$\mu_{T,1}$ = 0,0008691 [kg/m-s]	$\mu_{T,2}$ = 0,0008744 [kg/m-s]	$\mu_{T,3}$ = 0,0008803 [kg/m-s]
$\mu_{T,4}$ = 0,0008868 [kg/m-s]	$\mu_{T,5}$ = 0,000894 [kg/m-s]	$\mu_{T,m}$ = 0,0009524 [kg/m-s]	$\mu_{T,ref}$ = 0,00107 [kg/m-s]	$\nu_{T,1}$ = 8,526E-07 [m^2/s]	$\nu_{T,2}$ = 8,562E-07 [m^2/s]
$\nu_{T,3}$ = 8,601E-07 [m^2/s]	$\nu_{T,4}$ = 8,644E-07 [m^2/s]	$\nu_{T,5}$ = 8,691E-07 [m^2/s]	$\nu_{T,m}$ = 9,325E-07 [m^2/s]	n_e = 5 [-]	n_m = 5 [-]
n_p = 1 [-]	$P_{eff,1}$ = 21,78 [bar]	$P_{eff,2}$ = 19,68 [bar]	$P_{eff,3}$ = 17,07 [bar]	$P_{eff,4}$ = 14,32 [bar]	$P_{eff,5}$ = 11,43 [bar]

RESULTS FROM RO CALCULATION BY EES -2

n_p = 1 [-]	$P_{eff,1}$ = 21,78 [bar]	$P_{eff,2}$ = 19,68 [bar]	$P_{eff,3}$ = 17,07 [bar]	$P_{eff,4}$ = 14,32 [bar]	$P_{eff,5}$ = 11,43 [bar]
$P_{e,m}$ = 25,63 [bar]	P_{LP} = 1 [bar]	P_{LP} = 100 [kPa]	P_m = 55 [bar]	P_o = 51 [bar]	$P_{o,1}$ = 50,5 [bar]
$P_{o,2}$ = 50,31 [bar]	$P_{o,3}$ = 50,15 [bar]	$P_{o,4}$ = 50 [bar]	$P_{o,5}$ = 49,87 [bar]	P_o = 5050 [kPa]	$P_{Permeate}$ = 1 [bar]
P_{PX} = 44,88 [bar]	P_r = 49,75 [bar]	$P_{r,1}$ = 50,31 [bar]	$P_{r,2}$ = 50,15 [bar]	$P_{r,3}$ = 50 [bar]	$P_{r,4}$ = 49,87 [bar]
$P_{r,5}$ = 49,75 [bar]	$P_{r,m}$ = 54,68 [bar]	Q_f = 28,75 [m^3/day]	$Q_{f,1}$ = 1198 [L/h]	$Q_{f,2}$ = 1102 [L/h]	$Q_{f,3}$ = 1014 [L/h]
$Q_{f,4}$ = 932,8 [L/h]	$Q_{f,5}$ = 858,2 [L/h]	$Q_{f,m}$ = 1198 [L/h]	Q_p = 11,59 [m^3/day]	$Q_{p,1}$ = 95,83 [L/h]	$Q_{p,2}$ = 88,17 [L/h]
$Q_{p,3}$ = 81,11 [L/h]	$Q_{p,4}$ = 74,62 [L/h]	$Q_{p,5}$ = 68,65 [L/h]	$Q_{p,m}$ = 95,83 [L/h]	Q_r = 17,16 [m^3/day]	$Q_{r,1}$ = 1102 [L/h]
$Q_{r,2}$ = 1014 [L/h]	$Q_{r,3}$ = 932,8 [L/h]	$Q_{r,4}$ = 858,2 [L/h]	$Q_{r,5}$ = 789,5 [L/h]	$Q_{r,m}$ = 1102 [L/h]	R = 0,08314 [L*bar/(K*mol)]
Rej = 99,6 [%]	Rej_1 = 99,7 [%]	Rej_2 = 99,66 [%]	Rej_3 = 99,61 [%]	Rej_4 = 99,54 [%]	Rej_5 = 99,42 [%]
Rej_m = 99,78 [%]	Re_1 = 250,2 [-]	Re_2 = 229,3 [-]	Re_3 = 210 [-]	Re_4 = 192,2 [-]	Re_5 = 175,8 [-]
Re_m = 312 [-]	ρ_{sw1} = 1021 [kg/m^3]	ρ_{sw2} = 1023 [kg/m^3]	ρ_{sw3} = 1026 [kg/m^3]	ρ_{sw4} = 1028 [kg/m^3]	ρ_{sw5} = 1031 [kg/m^3]
$\rho_{sw,m}$ = 1024 [kg/m^3]	RR = 40,32 [%]	RR_1 = 8 [%]	RR_2 = 8 [%]	RR_3 = 8 [%]	RR_4 = 8 [%]
RR_5 = 8 [%]	RR_m = 8 [%]	sbf = 0,00279 [m]	Sc_1 = 401,1 [-]	Sc_2 = 405,2 [-]	Sc_3 = 409,8 [-]
Sc_4 = 414,9 [-]	Sc_5 = 420,5 [-]	Sc_m = 559,5 [-]	SEC = 2,3080 [kWh/m^3]	Sh_1 = 209,9 [-]	Sh_2 = 198,6 [-]
Sh_3 = 187,9 [-]	Sh_4 = 177,8 [-]	Sh_5 = 168,2 [-]	Sh_m = 271,8 [-]	S_1 = 3 [m^2]	S_2 = 3 [m^2]
S_3 = 3 [m^2]	S_4 = 3 [m^2]	S_5 = 3 [m^2]	S_m = 2,2 [m^2]	T = 29,1 [C]	TMP_1 = 49,41 [bar]
TMP_2 = 49,23 [bar]	TMP_3 = 49,07 [bar]	TMP_4 = 48,94 [bar]	TMP_5 = 48,81 [bar]	TMP_m = 53,84 [bar]	T_m = 25 [C]
T_o = 25 [C]	u_1 = 0,15 [m/s]	u_2 = 0,138 [m/s]	u_3 = 0,1269 [m/s]	u_4 = 0,1168 [m/s]	u_5 = 0,1074 [m/s]
u_m = 0,2045 [m/s]	w_1 = 3,125 [m]	w_2 = 3,125 [m]	w_3 = 3,125 [m]	w_4 = 3,125 [m]	w_5 = 3,125 [m]
$W_{feedboosterpump}$ = 0,04851 [kW]	$W_{feedHPpump}$ = 0,9036 [kW]	w_m = 2,292 [m]	$W_{recirculpump}$ = 0,1627 [kW]	W_{total} = 1,115 [kW]	

- **Appendix B – Mathematical equation model at EES for RO desalination system**

"CALCULATING PV-RO MODEL ------- by: Habibie Muhammad Ega"

"ASSUMPTIONS AND NOTE"

"Assumption ------ Mass Transfer Through RO Membrane"
"- Darcy's law was valid for the transport of water through the membrane.
- Osmotic pressure was proportional to the salt concentration (Van't Hoff Law).
- A single solute system (NaCl was considered).
- Thin film theory was applicable for concentration polarization effect.
- The permeate water was immediately and completely mixed in the permeate channel.
- Fluid properties remained constant during filtration.
- The model did not take fouling of the RO membrane into account."

"Assumption ------ Hydrodynamics and the geometry of RO Module"
"- RO membrane module of constant geometry composed of a single unwound sheet (of the total surface area) of flat channels with spacers.
- Negligible curvature effect of the RO membrane and spacers.
- Negligible pressure drop in permeate side.
- Negligible axial concentrate velocity and tangential permeate velocity in their respective channels."

"---------MODULE SPECIFICATION---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Eb - Activation Energy [kJ/mol]; Rej - Rejection Rate [%
_f_ - Feed; _p_ - Permeate; _m - Manufacturer Data; T_ref - Reference Temperature"

```
"Module Specification: 2540-SHF"
C_f_m = 32 [g/L]                    "Feed Salt Concentration from Manufacturer"
S_m = 2,2 [m^2]                     "Membrane Surface Area from Manufacturer"
P_m = 55 [bar]                      "Feed Applied Pressure from Manufacturer"
T_m = 25 [C]                        "Temperature of Test from Manufacturer"
RR_m = 8 [%]                        "Recovery Rate from Manufacturer"
Q_p_m = 95,83 [L/h]                 "Permeate Flow Rate from Manufacturer"
P_Permeate = 1 [bar]                "Atmospheric Pressure at Permeate"

"Geometric Parameters: for All CSM Products"
h_b = 0,71*10^(-3) [m]              "The Thickness of the Spacer"
sbf = 2,79*10^(-3) [m]              "The Space Between Strands"
L = 0,96 [m]                        "The Length of the Active Membrane Surface"

"Viscosity"
MU_T_ref = sw_viscosity(20 [C]; 32)      "Reference Dynamic Viscosity at T = 20 C and S = 32 g/kg"
MU_T_m = sw_viscosity(T_m; 32)   "Dynamic Viscosity at T= T_m and S = 32 g/kg"
NU_T_m = sw_kviscosity(T_m; 32)  "Kinematic Viscosity at T = T_m and S = 32 g/kg"

"Diffusitivity Coefficient"
T_o = 25 [C]                        "Reference Temperature"
D_T_ref = 1,484*10^(-9) [m^2/s]     "Reference Diffusitivity Coefficient at T = 25 C from Monnot et al. paper"

"Solvent & Solute Permeability Reference Data"
A_T_ref = 1,63 [L/(h*bar*m^2)]      "Pure Water Permeability at T = 20 C"
B_m = 2,8*10^(-8)*convert(m/s;m/h)  "Solute Permeability at T = 20 C"
B_ref = -2290 [1/K]      "Eb (Activation Energy)/R (Gas Constant) from CSM Software"
```

```
"Others Data"
i = 2 [-]                                          "Number of ions (NaCl)"
R = 0,08314472 [L*bar/(K*mol)]                     "Ideal Gas Constant"
RHO_sw_m = sw_density(T_m; 32; P_m*convert(bar;MPa)) "Density Seawater using Module Specification"

"Diffusitivity Coefficient"
D_m = (T_m/T_o)*(MU_T_ref/MU_T_m)*D_T_ref "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"


"---------CALCULATION WITH MODULE SPECIFICATION DATA (A & B Calculation)---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
 _f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Solvent and Solute Permeability Coefficient"
A_m = A_T_ref*(MU_T_ref/MU_T_m) "Solvent Permeability (Obtained Solvent Permeability at Ref. Temp.)"
B_m = B_o*exp(B_ref/(converttemp(C;K;20 [C]))) "Solute Permeability (Obtained Solute Permeability Constant)"

"Mass Transfer Coefficient"
Re_m = RHO_sw_m*u_m*d_h_m/MU_T_m       "Reynolds Number"
Sc_m = NU_T_m/D_m                      "Schmidt Number"
Sh_m = k_m*d_h_m/D_m        "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_m = (-41,06*G^2+22,9*G-2,52)*((Re_m/0,71)^0,65-1,36)*Sc_m^(1/3) "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
G = h_b/sbf                            "Geometric Spacer Parameter"
d_h_m = 4*((w_m*h_b)/(2*(w_m+h_b)))    "Hydraulic Diameter"
u_m = (Q_f_m*10^(-3)/3600)/(w_m*h_b)   "Axial Velocity in Feed Channel"
w_m = S_m/L                  "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_m = A_m*P_e_m                        "Solvent Flux with Manufacturer Data"
P_e_m = TMP_m-DELTA_PHI_m     "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_m = i*((C_m_m/58,44 [g/mol])-(C_p_m/58,44 [g/mol]))*R*(converttemp(C;K;T_m)) "Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
TMP_m = ((P_m+P_r_m)/2)-P_Permeate
exp((J_m*10^(-3)/3600)/k_m) = (C_m_m-C_p_m)/(C_f_m-C_p_m) "Concentration Polarization Equation with Manufacturer Data"
((J_m*C_p_m/B_m)/1000) = C_m_m-C_p_m    "Solute Transport Equation with Manufacturer Data"
Rej_m/100 = 1-(C_p_m/C_f_m)     "Rejection Rate Equation with Manufacturer Data"
RR_m/100 = Q_p_m/Q_f_m          "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_m = Q_p_m+Q_r_m                    "Flow Rate Balance"
Q_f_m*C_f_m = Q_p_m*C_p_m+Q_r_m*C_r_m  "Concentration Balance"

"Pressure Drop"
DELTA_P_m = (f_m*u_m^2/(2*d_h_m))*L    "Pressure Drop Inside the Module (or in an element of length dL)"
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f_m = ((1493/Re_m)+6,6)*G^1,19                    "Darcy Friction Factor for Pressure Drop"
P_r_m = P_m-(DELTA_P_m*convert(kPa;bar))  "Pressure at Rejection Side"

"---------INLET VARIABLES FOR ELEMENT 1---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; T - Temperature [C]
 _f - Feed; _T - Variable Value at Selection Temperature"

"Initial Conditions ------ 2540-SHF"
C_f_1 = 31 [g/L]                                  "Feed Salt Concentration"
S_1 = 3 [m^2]                                     "Area of Membrane"
T = 29,1 [C]                                      "Feed Water Temperature"
P_o_1 = 50,5 [bar]                                "Applied Pressure"
Q_p_1 = 95,8333 [L/h]                             "Permeate Flow Rate for 10 m3/day"
RR_1 = 8 [%]                             "Possible Recovery Ratio for this Configuration"

"Viscosity"
MU_T_1 = sw_viscosity(T; 31 [g/kg])   "Dynamic Viscosity at T = 25 C and S = 32 g/kg"
NU_T_1 = sw_kviscosity(T; 31 [g/kg])  "Kinematic Viscosity at T = 25 C and S = 32 g/kg"

"Solvent and Solute Permeability Calculation"
A_1 = A_T_ref*(MU_T_ref/MU_T_1)                   "Solvent Permeability at Tref = 20 C"
B_1 = B_o*exp(B_ref/(converttemp(C;K;T)))         "Solute Permeability"

"Other Data"
RHO_sw1= sw_density(T; 31 [g/kg]; P_o_1*convert(bar;MPa)) "Density Seawater using Module Specification"

"Diffusitivity Coefficient"
D_1 = (T/T_o)*(MU_T_ref/MU_T_1)*D_T_ref     "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"


"---------CALCULATION FOR ELEMENT 1---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
_f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Mass Transfer Coefficient"
Re_1 = RHO_sw1*u_1*d_h_1/MU_T_1                   "Reynolds Number"
Sc_1 = NU_T_1/D_1                                 "Schmidt Number"
Sh_1 = k_1*d_h_1/D_1       "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_1 = (-41,06*G^2+22,9*G-2,52)*((Re_1/0,71)^0,65-1,36)*Sc_1^(1/3)   "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
d_h_1 = 4*((w_1*h_b)/(2*(w_1+h_b)))               "Hydraulic Diameter"
u_1 = (Q_f_1*10^(-3)/3600)/(w_1*h_b)              "Axial Velocity in Feed Channel"
w_1 = S_1/L                          "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_1 = A_1*P_eff_1                                 "Solvent Flux with Manufacturer Data"
P_eff_1 = TMP_1-DELTA_PHI_1      "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_1 = i*((C_m_1/58,44 [g/mol])-(C_p_1/58,44 [g/mol]))*R*converttemp(C;K;T)
"Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
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TMP_1 = ((P_o_1+P_r_1)/2)-P_Permeate "Transmembrane Pressure on First Stage"
exp((J_1*10^(-3)/3600)/k_1) = (C_m_1-C_p_1)/(C_f_1-C_p_1) "Concentration Polarization Equation with Manufacturer Data"
(J_1*C_p_1/B_1)/1000 = C_m_1-C_p_1 "Solute Transport Equation with Manufacturer Data"
Rej_1/100 [%] = 1-(C_p_1/C_f_1) "Rejection Rate Equation with Manufacturer Data"
RR_1/100 [%] = Q_p_1/Q_f_1 "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_1 = Q_p_1+Q_r_1 "Reverse Osmosis Unit Flow Rate Balance"
Q_f_1*C_f_1 = Q_p_1*C_p_1+Q_r_1*C_r_1 "Reverse Osmosis Unit Concentration Balance"

"Pressure Drop"
DELTA_P_1 = (f_1*u_1^2/(2*d_h_1))*L "Pressude Drop Inside the Module (or in an element of length dL)"
f_1 = ((1493/Re_1)+6,6)*G^1,19 "Darcy Friction Factor for Pressure Drop"
P_r_1 = P_o_1-(DELTA_P_1***convert**(kPa;bar)) "Solution Pressure on Rejection Side"

"---------INLET VARIABLES FOR ELEMENT 2---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; T - Temperature [C]
_f - Feed; _T - Variable Value at Selection Temperature"

"Initial Conditions ------ 2540-SHF"
C_f_2 = C_r_1 "Feed Salt Concentration"
Q_f_2 = Q_r_1 "Feed Flow Rate"
P_o_2 = P_r_1 "Applied Pressure"
RR_2 = 8 [%] "Recovery Ratio"
S_2 = 3 [m^2] "Area of Single Membrane"

"Viscosity"
MU_T_2 = **sw_viscosity**(T; 33,69 [g/kg]) "Dynamic Viscosity at S= Rejection Concentration from 1st Stage"
NU_T_2 = **sw_kviscosity**(T; 33,69 [g/kg]) "Kinematic Viscosity at S=Rejection Concentration from 1st Stage"

"Solvent and Solute Permeability Calculation"
A_2 = A_T_ref*(MU_T_ref/MU_T_2) "Solvent Permeability of Membrane Characteristic at 2nd Stage"
B_2 = B_o***exp**(B_ref/**converttemp**(C;K;T)) "Solute Permeability of Membrane Characteristic at 2nd Stage"

"Density"
RHO_sw2 = **sw_density**(T; 33,69 [g/kg]; P_o_2***convert**(bar;MPa)) "Density Seawater for 2nd Stage"

"Diffusitivity Coefficient"
D_2 = (T/T_o)*(MU_T_ref/MU_T_2)*D_T_ref "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"

"---------CALCULATION FOR ELEMENT 2---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
_f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Mass Transfer Coefficient"

Re_2 = RHO_sw2*u_2*d_h_2/MU_T_2 "Reynolds Number"
Sc_2 = NU_T_2/D_2 "Schmidt Number"
Sh_2 = k_2*d_h_2/D_2 "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_2 = (-41,06*G^2+22,9*G-2,52)*((Re_2/0,71)^0,65-1,36)*Sc_2^(1/3) "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
d_h_2 = 4*((w_2*h_b)/(2*(w_2+h_b))) "Hydraulic Diameter"
u_2 = (Q_f_2*10^(-3)/3600)/(w_2*h_b) "Axial Velocity in Feed Channel"
w_2 = S_2/L "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_2 = A_2*P_eff_2 "Solvent Flux with Manufacturer Data"
P_eff_2 = TMP_2-DELTA_PHI_2 "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_2 = i*((C_m_2/58,44 [g/mol])-(C_p_2/58,44 [g/mol]))*R***converttemp**(C;K;25 [C]) "Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
TMP_2 = ((P_o_2+P_r_2)/2)-P_Permeate "Transmembrane Pressure on Second Stage"
exp((J_2*10^(-3)/3600)/k_2) = (C_m_2-C_p_2)/(C_f_2-C_p_2) "Concentration Polarization Equation with Manufacturer Data"
(J_2*C_p_2/B_2)/1000 = C_m_2-C_p_2 "Solute Transport Equation with Manufacturer Data"
Rej_2/100 [%] = 1-(C_p_2/C_f_2) "Rejection Rate Equation with Manufacturer Data"
RR_2/100 [%] = Q_p_2/Q_f_2 "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_2 = Q_p_2+Q_r_2 "Reverse Osmosis Unit Flow Rate Balance"
Q_f_2*C_f_2 = Q_p_2*C_p_2+Q_r_2*C_r_2 "Reverse Osmosis Unit Concentration Balance"

"Pressure Drop"
DELTA_P_2 = (f_2*u_2^2/(2*d_h_2))*L "Pressude Drop Inside the Module (or in an element of length dL)"
f_2 = ((1493/Re_2)+6,6)*G^1,19 "Darcy Friction Factor for Pressure Drop"
P_r_2 = P_o_2-(DELTA_P_2***convert**(kPa;bar)) "Solution Pressure on Rejection Side"

"---------INLET VARIABLES FOR ELEMENT 3---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; T - Temperature [C]
_f - Feed; _T - Variable Value at Selection Temperature"

"Initial Conditions ------ 2540-SHF"
C_f_3 = C_r_2 "Feed Salt Concentration"
Q_f_3 = Q_r_2 "Feed Flow Rate"
P_o_3 = P_r_2 "Applied Pressure"
RR_3 = 8 [%] "Recovery Ratio"
S_3 = 3 [m^2] "Area of Single Membrane"

"Viscosity"
MU_T_3 = **sw_viscosity**(T; 36,61 [g/kg]) "Dynamic Viscosity at S= Rejection Concentration from 1st Stage"
NU_T_3 = **sw_kviscosity**(T; 36,61 [g/kg]) "Kinematic Viscosity at S=Rejection Concentration from 1st Stage"

"Solvent and Solute Permeability Calculation"
A_3 = A_T_ref*(MU_T_ref/MU_T_3) "Solvent Permeability of Membrane Characteristic at 2nd Stage"
B_3 = B_o***exp**(B_ref/**converttemp**(C;K;T)) "Solute Permeability of Membrane Characteristic at 2nd Stage"

"Density"

RHO_sw3 = **sw_density**(T; 36,61 [g/kg]; P_o_3***convert**(bar;MPa)) "Density Seawater for 2nd Stage"

"Diffusitivity Coefficient"
D_3 = (T/T_o)*(MU_T_ref/MU_T_3)*D_T_ref "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"

"---------CALCULATION FOR ELEMENT 3---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
_f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Mass Transfer Coefficient"
Re_3 = RHO_sw3*u_3*d_h_3/MU_T_3 "Reynolds Number"
Sc_3 = NU_T_3/D_3 "Schmidt Number"
Sh_3 = k_3*d_h_3/D_3 "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_3 = (-41,06*G^2+22,9*G-2,52)*((Re_3/0,71)^0,65-1,36)*Sc_3^(1/3) "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
d_h_3 = 4*((w_3*h_b)/(2*(w_3+h_b))) "Hydraulic Diameter"
u_3 = (Q_f_3*10^(-3)/3600)/(w_3*h_b) "Axial Velocity in Feed Channel"
w_3 = S_3/L "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_3 = A_3*P_eff_3 "Solvent Flux with Manufacturer Data"
P_eff_3 = TMP_3-DELTA_PHI_3 "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_3 = i*((C_m_3/58,44 [g/mol])-(C_p_3/58,44 [g/mol]))*R***converttemp**(C;K;25 [C]) "Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
TMP_3 = ((P_o_3+P_r_3)/2)-P_Permeate "Transmembrane Pressure on Second Stage"
exp((J_3*10^(-3)/3600)/k_3) = (C_m_3-C_p_3)/(C_f_3-C_p_3) "Concentration Polarization Equation with Manufacturer Data"
(J_3*C_p_3/B_3)/1000 = C_m_3-C_p_3 "Solute Transport Equation with Manufacturer Data"
Rej_3/100 [%] = 1-(C_p_3/C_f_3) "Rejection Rate Equation with Manufacturer Data"
RR_3/100 [%] = Q_p_3/Q_f_3 "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_3 = Q_p_3+Q_r_3 "Reverse Osmosis Unit Flow Rate Balance"
Q_f_3*C_f_3 = Q_p_3*C_p_3+Q_r_3*C_r_3 "Reverse Osmosis Unit Concentration Balance"

"Pressure Drop"
DELTA_P_3 = (f_3*u_3^2/(2*d_h_3))*L "Pressude Drop Inside the Module (or in an element of length dL)"
f_3 = ((1493/Re_3)+6,6)*G^1,19 "Darcy Friction Factor for Pressure Drop"
P_r_3 = P_o_3-(DELTA_P_3***convert**(kPa;bar)) "Solution Pressure on Rejection Side"

"---------INLET VARIABLES FOR ELEMENT 4---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; T - Temperature [C]
_f - Feed; _T - Variable Value at Selection Temperature"

"Initial Conditions ------ 2540-SHF"
C_f_4 = C_r_3 "Feed Salt Concentration"

Q_f_4 = Q_r_3 "Feed Flow Rate"
P_o_4 = P_r_3 "Applied Pressure"
RR_4 = 8 [%] "Recovery Ratio"
S_4 = 3 [m^2] "Area of Single Membrane"

"Viscosity"
MU_T_4 = **sw_viscosity**(T; 39,79 [g/kg]) "Dynamic Viscosity at S= Rejection Concentration from 1st Stage"
NU_T_4 = **sw_kviscosity**(T; 39,79 [g/kg]) "Kinematic Viscosity at S=Rejection Concentration from 1st Stage"

"Solvent and Solute Permeability Calculation"
A_4 = A_T_ref*(MU_T_ref/MU_T_4) "Solvent Permeability of Membrane Characteristic at 2nd Stage"
B_4 = B_o***exp**(B_ref/**converttemp**(C;K;T)) "Solute Permeability of Membrane Characteristic at 2nd Stage"

"Density"
RHO_sw4 = **sw_density**(T; 39,79 [g/kg]; P_o_4***convert**(bar;MPa) "Density Seawater for 2nd Stage"

"Diffusitivity Coefficient"
D_4 = (T/T_o)*(MU_T_ref/MU_T_4)*D_T_ref "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"

"---------CALCULATION FOR ELEMENT 4---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
_f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Mass Transfer Coefficient"
Re_4 = RHO_sw4*u_4*d_h_4/MU_T_4 "Reynolds Number"
Sc_4 = NU_T_4/D_4 "Schmidt Number"
Sh_4 = k_4*d_h_4/D_4 "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_4 = (-41,06*G^2+22,9*G-2,52)*((Re_4/0,71)^0,65-1,36)*Sc_4^(1/3) "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
d_h_4 = 4*((w_4*h_b)/(2*(w_4+h_b))) "Hydraulic Diameter"
u_4 = (Q_f_4*10^(-3)/3600)/(w_4*h_b) "Axial Velocity in Feed Channel"
w_4 = S_4/L "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_4 = A_4*P_eff_4 "Solvent Flux with Manufacturer Data"
P_eff_4 = TMP_4-DELTA_PHI_4 "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_4 = i*((C_m_4/58,44 [g/mol])-(C_p_4/58,44 [g/mol]))*R***converttemp**(C;K;25 [C]) "Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
TMP_4 = ((P_o_4+P_r_4)/2)-P_Permeate "Transmembrane Pressure on Second Stage"
exp((J_4*10^(-3)/3600)/k_4) = (C_m_4-C_p_4)/(C_f_4-C_p_4) "Concentration Polarization Equation with Manufacturer Data"
(J_4*C_p_4/B_4)/1000 = C_m_4-C_p_4 "Solute Transport Equation with Manufacturer Data"
Rej_4/100 [%] = 1-(C_p_4/C_f_4) "Rejection Rate Equation with Manufacturer Data"
RR_4/100 [%] = Q_p_4/Q_f_4 "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_4 = Q_p_4+Q_r_4 "Reverse Osmosis Unit Flow Rate Balance"

Q_f_4*C_f_4 = Q_p_4*C_p_4+Q_r_4*C_r_4 "Reverse Osmosis Unit Concentration Balance"

"Pressure Drop"
DELTA_P_4 = (f_4*u_4^2/(2*d_h_4))*L "Pressude Drop Inside the Module (or in an element of length dL)"
f_4 = ((1493/Re_4)+6,6)*G^1,19 "Darcy Friction Factor for Pressure Drop"
P_r_4 = P_o_4-(DELTA_P_4***convert**(kPa;bar)) "Solution Pressure on Rejection Side"

"---------INLET VARIABLES FOR ELEMENT 5---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; T - Temperature [C]
_f - Feed; _T - Variable Value at Selection Temperature"

"Initial Conditions ------ 2540-SHF"
C_f_5 = C_r_4 "Feed Salt Concentration"
Q_f_5 = Q_r_4 "Feed Flow Rate"
P_o_5 = P_r_4 "Applied Pressure"
RR_5 = 8 [%] "Permeate Flow Rate for 2nd Stage 10 m3/day"
S_5 = 3 [m^2] "Area of Single Membrane"

"Viscosity"
MU_T_5 = **sw_viscosity**(T; 43,23 [g/kg]) "Dynamic Viscosity at S= Rejection Concentration from 1st Stage"
NU_T_5 = **sw_kviscosity**(T; 43,23 [g/kg]) "Kinematic Viscosity at S=Rejection Concentration from 1st Stage"

"Solvent and Solute Permeability Calculation"
A_5 = A_T_ref*(MU_T_ref/MU_T_5) "Solvent Permeability of Membrane Characteristic at 2nd Stage"
B_5 = B_o***exp**(B_ref/**converttemp**(C;K;T)) "Solute Permeability of Membrane Characteristic at 2nd Stage"

"Density"
RHO_sw5 = **sw_density**(T; 43,23 [g/kg]; P_o_5***convert**(bar;MPa)) "Density Seawater for 2nd Stage"

"Diffusitivity Coefficient"
D_5 = (T/T_o)*(MU_T_ref/MU_T_5)*D_T_ref "Diffusitivity Coefficient Equation from the Strokes-Einstein Relationship"

"---------CALCULATION FOR ELEMENT 5---------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Solute Concentration [g/L]; RR - Recovery Percentage [%]; P - Pressure [bar]; MU - Dynamic Viscosity [kg/m-s]; D - Diffusitivity Coefficient [m^2/s]; Sh - Sherwood Number; Re - Reynolds Number; Sc - Schmidt Number; TMP - Transmembrane Pressure; Rej - Rejection Rate [%]
_f_ - Feed; _p_ - Permeate; _r_ - Brine or Concentration; _m_ - membrane; _m - Manufacturer Data; _T - Temperature at Initial Conditions; _T_ref - Reference Temperature"

"Mass Transfer Coefficient"
Re_5 = RHO_sw5*u_5*d_h_5/MU_T_5 "Reynolds Number"
Sc_5 = NU_T_5/D_5 "Schmidt Number"
Sh_5 = k_5*d_h_5/D_5 "Mass Transfer Equation with Diffusitivity Coefficient"
Sh_5 = (-41,06*G^2+22,9*G-2,52)*((Re_5/0,71)^0,65-1,36)*Sc_5^(1/3) "Mass Transfer Equation with Reynold and Schmidt Number"

"RO Geometry Module"
d_h_5 = 4*((w_5*h_b)/(2*(w_5+h_b))) "Hydraulic Diameter"

u_5 = (Q_f_5*10^(-3)/3600)/(w_5*h_b) "Axial Velocity in Feed Channel"
w_5 = S_5/L "Width of the Membrane with Manufacturer Data"

"RO Mass Transfer"
J_5 = A_5*P_eff_5 "Solvent Flux with Manufacturer Data"
P_eff_5 = TMP_5-DELTA_PHI_5 "Effective Pressure Equation with Manufacturer Data"
DELTA_PHI_5 = i*((C_m_5/58,44 [g/mol])-(C_p_5/58,44 [g/mol]))*R***converttemp**(C;K;25 [C]) "Differential Osmotic Pressure (Van't Hoff's Law) with Manufacturer Data"
TMP_5 = ((P_o_5+P_r_5)/2)-P_Permeate "Transmembrane Pressure on Second Stage"
exp((J_5*10^(-3)/3600)/k_5) = (C_m_5-C_p_5)/(C_f_5-C_p_5) "Concentration Polarization Equation with Manufacturer Data"
(J_5*C_p_5/B_5)/1000 = C_m_5-C_p_5 "Solute Transport Equation with Manufacturer Data"
Rej_5/100 [%] = 1-(C_p_5/C_f_5) "Rejection Rate Equation with Manufacturer Data"
RR_5/100 [%] = Q_p_5/Q_f_5 "Recovery Rate Equation with Manufacturer Data"

"Mass Balance"
Q_f_5 = Q_p_5+Q_r_5 "Reverse Osmosis Unit Flow Rate Balance"
Q_f_5*C_f_5 = Q_p_5*C_p_5+Q_r_5*C_r_5 "Reverse Osmosis Unit Concentration Balance"

"Pressure Drop"
DELTA_P_5= (f_5*u_5^2/(2*d_h_5))*L "Pressude Drop Inside the Module (or in an element of length dL)"
f_5 = ((1493/Re_5)+6,6)*G^1,19 "Darcy Friction Factor for Pressure Drop"
P_r_5 = P_o_5-(DELTA_P_5***convert**(kPa;bar)) "Solution Pressure on Rejection Side"

"-----------GLOBAL SYSTEM CALCULATION----------"
"NOMENCLATURE"
"Q - Volumetric Flow Rate [L/h]; C - Concentration [g/L]; n - number of elements/Pressure Vessel [-]
_e - elements; _p - Pressure Vessel; _m - Total Number of Elements; _f - Feed; _p - Permeate; _r - Rejection"

"RO System Specification"
n_e = 5 [-] "Number of Elements"
n_p = 1 [-] "Number of Pressure Vessels"
n_m = n_e*n_p "Total Number of Elements in the System"

"Global Flow Rate"
Q_f = (Q_f_1*n_p)***convert**(l/h;m^3/day) "Global Feed Flow Rate"
Q_p = ((Q_p_1+Q_p_2+Q_p_3+Q_p_4+Q_p_4+Q_p_5)*n_p)***convert**(l/h;m^3/day) "Global Permeate Flow Rate"
Q_r = (Q_f-Q_p)*n_p "Global Rejection Flow Rate"

"Global Concentration"
C_f = C_f_1 "Global Feed Concentration"
C_r = C_r_5 "Global Rejection Concentration"

"Global Pressure"
P_o = P_o_1 "Feed Pressure"
P_r = P_r_5 "Rejection Pressure"

"Global Mass Balances"
Q_f*C_f = Q_p*C_p+(Q_r_5***convert**(l/h;m^3/day))*C_r "Global Permeate Concentration"

"Global System Performance"
RR = (Q_p/Q_f)*100 [%] "Recovery Rate of System"
Rej = (1-(C_p/C_f))*100 [%] "Rejection Rate of System"

"---------ENERGY CALCULATION---------"
"NOMENCLATURE"

"Q - Volumetric Flow Rate [L/h]; ETA - Efficiency [%]; P - Pressure [bar]; W - Power Consumption [kW]
_HP - High Pressure Pump; _Booster - Booster Pump; _Motor - Electrical Motor; _PX - Pressure Exchanger; _LP- Low Pressure"

"Energy Consumption Parameters"
ETA_HP = 75 [%] "High Pressure Pump Efficiency from Lu et al. Paper"

ETA_Booster = 70 [%] "Booster Pressure Pump Efficiency from Lu et al. Paper"
ETA_Motor = 98 [%] "Electrical Motor Efficiency from Lu et al. Paper"
ETA_PX = 90 [%] "Pressure Exchanger Efficiency from Lu et al. Paper"
P_LP = 1 [bar] "Residual Low Pressure from Danfoss Manufacturer"
P_LP_Prime = P_LP***convert**(bar;kPa) "Residual Low Pressure with kPa unit"
P_o_Prime = P_o***convert**(bar;kPa) "Feed Pressure on 1st Stage with kPa unit"

"Power Consumption Calculation"
W_feedboosterpump = (P_LP_Prime*Q_f***convert**(m^3/day;m^3/s))/((ETA_Booster/100 [%])*(ETA_Motor/100 [%])) "Feed Booster Pump Power Consumption"
W_feedHPpump = ((P_o_Prime-P_LP_Prime)*((Q_f-Q_r)***convert**(m^3/day;m^3/s)))/((ETA_HP/100 [%])*(ETA_Motor/100 [%])) "Feed High Pressure Pump Power Consumption"
W_recirculpump = ((P_o_Prime-P_PX***convert**(bar;kPa))*(Q_r***convert**(m^3/day;m^3/s)))/((ETA_Booster/100 [%])*(ETA_Motor/100 [%])) "Recirculation Pump Power Consumption"
ETA_PX/100 [%] = ((P_PX-P_LP)*Q_r)/((P_r-P_LP)*Q_r) "Pressure after PX Component"
W_total = W_feedboosterpump+W_feedHPpump+W_recirculpump "Total Power Consumption"

"Specific Energy Consumption"
SEC = W_total/(Q_p***convert**(m^3/day;m^3/h)) "Specific Energy Consumption of The System"

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